UNIVERSIDAD POLITÉCNICA DE MADRID

ESCUELA TÉCNICA SUPERIOR
DE INGENIEROS DE TELECOMUNICACIÓN

MASTER OF SCIENCE IN NEUROTECHNOLOGY

MASTER´S THESIS

DESIGN AND IMPLEMENTATION OF A HUMAN COMPUTER INTERFACE SYSTEM FOR SENSORY FEEDBACK IN UPPER-LIMB PROSTHESIS USERS

MARTA ZARAGOZA RODRÍGUEZ-PATÓN

2025

Master of Science in Neurotechnology

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Title: Design and implementation of a human computer interface system for sensory feedback in upper-limb prosthesis users

Author: Marta Zaragoza Rodríguez-Patón

Technical Supervisor: Cristina Montero Pardo

Academic Supervisor: Blanca Larraga García

Department: Departamento de Robótica y Control

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Resumen

Las personas con amputación de miembro superior mencionan la falta de retroalimentación sensorial como una de las principales limitaciones de las prótesis comerciales. Esta ausencia dificulta aplicar fuerzas de agarre de forma segura y realizar manipulaciones finas. En otras palabras, al no recibir señales fisiológicas desde la extremidad hacia el cerebro, la prótesis no se integra completamente en la percepción corporal del usuario, lo que limita su control y confianza.

El objetivo de este proyecto es desarrollar e implementar un sistema de retroalimentación sensorial en tiempo real, basado en estimulación eléctrica, para mejorar la capacidad de los amputados de manipular objetos con mayor precisión y seguridad. Además, permitirá distinguir diferentes tipos de materiales según su rigidez, acercando la prótesis a una función más natural e intuitiva.

Los patrones generados por el cuerpo humano pueden categorizarse en distintos comandos para controlar dispositivos externos, permitiendo la comunicación entre el ser humano y las máquinas mediante interfaces persona-ordenador (Human–Computer Interfaces, HCI). Aunque en este proyecto no se han utilizado señales biológicas para el control de la prótesis, el sistema desarrollado está concebido como un módulo complementario que podría integrarse en prótesis mioeléctricas.

El sistema se basa en la medición de la fuerza de agarre ejercida por un brazo robótico, emulando el comportamiento de una prótesis real. Esta información se utiliza para aplicar estímulos eléctricos de distinta intensidad sobre los músculos residuales del brazo, generando sensaciones en función de la fuerza aplicada.

Para su implementación y validación, se ha utilizado un robot PhantomX Reactor como simulación del brazo protésico, equipado con sensores de fuerza e integrado con un dispositivo personalizado llamado EAST, capaz de adquirir señales EMG y de estimular músculos. El objetivo final es cerrar el bucle de control en las prótesis mioeléctricas mediante una retroalimentación somatosensorial artificial en tiempo real, como método no invasivo para transmitir al paciente el nivel de fuerza que está ejerciendo.

El sistema integrado fue validado experimentalmente en condiciones controladas de laboratorio. Los resultados preliminares indican una respuesta prometedora por parte del usuario en cuanto a la percepción sensorial. Este trabajo representa un avance hacia el desarrollo de prótesis de miembro superior más funcionales y sensibles, con el deseo final de mejorar la calidad de vida de los pacientes.

Palabras clave

Retroalimentación sensorial, Estimulación eléctrica no invasiva, Prótesis de extremidad superior, Control retroalimentado en lazo cerrado.

Abstract

People with upper-limb amputations often mention the lack of sensory feedback as one of the main limitations of commercial prostheses. This absence makes it difficult to apply grip forces safely and to perform fine manipulations. In other words, the lack of physiological signals from the limb back to the brain, prevents the prosthesis from being fully integrated into the user's body perception, which limits both control and confidence.

The objective of this project is to develop and implement a real-time sensory feedback system based on electrical stimulation, aimed at improving the ability of amputees to manipulate objects with greater precision and safety. Furthermore, the system is designed to enable the distinction between different types of materials according to their stiffness, bringing prosthetic function closer to a more natural and intuitive experience.

Sensory feedback is mentioned by upper-limb amputees as one of the main missing features of commercial prostheses, as they cannot perform confident grip forces or fine manipulations. The lack of physiological feedback from the remaining extremity to the brain, prevents the correct integration of the prosthesis into the body perception of the person.

This project aims to develop and implement a real-time sensory feedback system based on electrical stimulation to enhance the ability of amputees to manipulate objects with their prosthesis with greater precision and confidence, as well as to identify different types of materials based on their stiffness.

Human-generated patterns can be categorized into different commands to control the activities of external devices allowing the communication between man and machines via a human–computer interface (HCI). Although biological signals were not used to control prostheses, this project focuses on being a complementary module that could be integrated into myoelectrical prostheses.

The system relies on the measurement of the grip force exerted by a robot arm, emulating the behavior of a real prosthetic device. This information will be used to apply electrical stimuli of varying intensity to the residual muscles of the arm to generate sensations depending on the applied force.

For the implementation and testing, a PhantomX Reactor Robot was used to simulate the bionic arm with integrated force sensors and a custom-made device called EAST, capable of both acquiring EMG signals and stimulating muscles. The end goal is to close the control loop in myoelectric prostheses by providing rela-time artificial somatosensory feedback as a non-invasive method to convey to the patient the level of force they are exerting.

The fully integrated system was experimentally validated under controlled laboratory conditions. Preliminary results indicate a promising user response in terms of sensory perception.

This work represents a step forward in the development of more functional and responsive upper-limb prostheses with the final to wish to improve the lives of patients.

Keywords

Sensory feedback, Non-invasive electrical stimulation, Upper-limb prosthesis, Closed-loop control.

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Glossary

EAST - Electrical Afferent Stimulation for Tremor

FSR - Force Sentitive Resistor

EMG - Electromyography

EEG - Electroencephalography

HCI - Human-Computer Interface

TENS - Transcutaneous Electrical Nerve Stimulation

DOF - Degrees Of Freedom

IDE - Integrated Development Environment

ADC - Analog-to-Digital Converter

1. Introduction and objectives

1.1 Introduction

Upper-limb prostheses are devices that aim to replace morphologically and functionally the hand and part of the arm that is lost due to an amputation. The flexible musculoskeletal structure of the human arm does not only allow for precise reaching, grasping and manipulation of objects, but also supplies with a network of natural sensors. These provide proprioceptive (perception of own position and neuromuscular control and movement) and exteroceptive (perception of external stimuli through the senses) information to the brain, for smooth, effortless, and highly adaptive execution of these movements.

The lack of inclusion of these sensory systems remains a fundamental limitation in prosthetic devices, despite the significant advances made in recent years. Upper limb prostheses have improved significantly by offering better mechanical functionalities and control strategies, from passive arm prostheses or body-powered ones, to myoelectric and EEG-based prosthetic arms [1]. In recent years, this field has also managed to incorporate additional advanced sensing technologies and features such as haptic feedback, vibrations, beepers, buttons and lights. These improvements aim to integrate a feedback interface that conveys the sense of touch and force, for better motor control and the embodiment of the bionic arm [2, 3, 4]. However, these technologies are still at an early stage of development and adoption in society, mainly due to their high cost and little accessibility.

The loss of an upper limb, combined with the challenges of insufficient integration of a prosthetic device, has far-reaching consequences and profound effects on a person's life. Those affected are faced with difficulties when executing everyday tasks, are reluctant to return to their workplace, have reduced social participation, and potentially also suffer from phantom limb pain [5].

These limitations can be caused by variables such as lack of comfort, the weight of the prosthesis or its function, leading to discomfort, rejection or even abandonment [6]. As a result, one of the challenges facing prosthetic design and engineering is to restore the missing sensory function lost due to the amputation of the hand/arm [7].

A promising strategy is **closing the control loop** in **myoelectric prostheses** by providing patients with **artificial somatosensory feedback** so that they can get a feeling of what they are doing with the hand. In this way, their interactions with the environment will be more **intuitive** and **natural**.

The so-called EMG feedback is a modality that consists of the transmission of the generated and processed myoelectric signals to the prosthesis and simultaneously to the user as feedback information [8]. However, there is an open challenge when developing closed-loop prosthetic systems as there are many potential methods and technologies to implement somatosensory feedback [9].

Recent research has demonstrated the benefits of providing users with EMG feedback for controlling myoelectric prostheses [5]. In this study, participants were asked to grasp and regulate the force applied to objects of three different stiffness levels while operating a prosthetic hand. The researchers compared performance under two conditions: conventional prosthesis control, which relies mainly on incidental cues such as vision or sound, and an augmented condition in which EMG activity was fed back to the user in real time. The results showed that when EMG feedback was available, participants achieved more accurate and consistent force regulation across all stiffness levels, even when they could rely on visual or auditory information about their performance. In other words, the additional feedback gave users a clearer and more reliable sense of how much force they were exerting. These findings provide strong evidence that EMG feedback can significantly enhance prosthesis control and support its potential integration into future closed-loop prosthetic systems.

In 2005, approximately 1.6 million people in the United States were estimated to have limb amputations, and this number is projected to double by 2050 [10]. Regarding upper-limb amputations, trauma is the most common cause, accounting for approximately 80% of acquired cases, particularly in males between the ages of 15 and 45 [10].

Amputations may be partial or complete, and can occur at different levels such as transradial, transhumeral, or partial hand amputations. Patients with upper-limb amputations often face persistent challenges even when using prosthetic devices: the lack of sensory feedback, difficulty judging grasping force, over-reliance on visual cues, reduced ability to perform fine motor tasks, issues with comfort, phantom limb pain, and in some cases, prosthesis abandonment due to frustration or limited functionality.

These figures highlight a real and growing need to improve the functionality of upper-limb prostheses, not only in terms of mechanical performance but also in sensory restoration. Providing tactile and proprioceptive feedback could enhance independence, reduce cognitive load, and ultimately increase prosthesis acceptance among users.

This project presents the development of a non-invasive sensory feedback system designed to provide users with real-time information about interaction with objects. These interactions include measuring the force applied to grasp objects with different materials. The system uses electrical stimulation applied to residual muscles in the upper limb to evoke tactile-like sensations in a safe and controlled manner. By translating signals from a prosthetic hand into somatosensory cues, this approach seeks to restore part of the missing feedback loop and to improve both, functionality and user experience in upper limb prostheses.

To fulfill this, a complex system with various elements will be developed. In the laboratory, we have robotic arms a gripper at the end, which will act as the prothesis of a person with an upper limb amputation. Inside the gripper, we have installed a sensor that will detect the force when it closes. This variability will determine the intensity of the stimulation the patient will receive, ruled by a tension generator called EAST. This synchrony will be orchestrated by an Arduino board which will power the sensor circuit and read the stimulation signal sent from the EAST device; as well as by a laptop running MATLAB R2023a and the Arduino IDE, which will serve to process the signals and control the system in real time.

As a result, we will obtain a coordinated sequence of events that will simulate the closed-loop interaction between a prosthetic hand and the environment, allowing the user to receive somatosensory feedback based on grip force through electrical stimulation. This system aims to mimic a more natural sensorimotor experience, potentially improving both functional performance and user embodiment.

1.2 Objectives

The overall aim of this Master's Thesis is to design, develop, and evaluate a non-invasive sensory feedback system to improve the user experience and functionality of myoelectric upper limb prostheses. The system seeks to provide real-time somatosensory feedback based on the interaction between a prosthetic hand and external objects, using electrical stimulation of residual limb muscles to elicit tactile-like sensations in the user, with the ultimate goal of closing the control loop of myoelectric prosthetic devices.

To accomplish this goal, the following objectives need to be fulfilled:

- Develop an electrical stimulation method to provide the user with feedback that corresponds to the exerted force in different scenarios.
- Implement a Human-Computer Interface control system that manages the interaction between a robotic arm, acting as the user's prosthesis, and the stimulation method.
- Develop the necessary software for real-time management of signal acquisition, signal processing, robotic actuation, force detection, and delivery of sensory feedback in an integrated and synchronous manner.
- Evaluate the effectiveness, reliability, and user perception of the feedback system through experimental tests in a controlled laboratory environment.

1.3 Structure of the document

This Master's Thesis is organized into six main chapters, each addressing a specific aspect of the work carried out:

Chapter 1. Introduction. Presents the motivation, context, and objectives of the project. It introduces the problem of sensory loss in upper-limb amputees, the limitations of current prosthetic devices, and the grounds for developing a non-invasive feedback system.

Chapter 2. Theoretical Framework. Reviews the background necessary to understand the project. It covers the somatosensory system, including primary sensory neurons, afferent fibers, mechanoreceptors, and the lemniscal pathway. It also discusses non-invasive sensory feedback approaches for prostheses and the concept of closed-loop myoelectric control.

Chapter 3. Development. Describes the design and implementation of the proposed system. The components of the setup, including the PhantomX Reactor robot, the Force Sensing Resistor (FSR), and the EAST stimulation device are presented in detail, along with the electronic circuitry, software integration, and overall control architecture.

Chapter 4. Results. Reports the outcomes of the experimental tests. The performance of the force sensor with different materials is characterized, and the relationship between grasping forces and stimulation patterns is analyzed. Results with a subject using the complete feedback loop are also presented.

Chapter 5. Discussion, Conclusions, and Future Work. Summarizes the main findings of the project, evaluates the extent to which the objectives were achieved, and reflects on the limitations. It also outlines possible directions for future work, including system improvements and further experimental validation.

Annexes. Contain supporting material, such as the financial budget, ethical considerations, detailed diagrams, and references to the developed code.

2. Theoretical framework

In order to understand the motivation and design choices behind this project, it is essential to first review the theoretical foundations on which it is based. The sense of touch and proprioception play a critical role in natural motor control, providing the brain with continuous information about the body's interaction with the environment. When an upper limb is lost, this flow of sensory information is disrupted, making it difficult for prosthesis users to achieve intuitive and precise control.

This section begins with an overview of the somatosensory system, describing its main components and pathways. These concepts are key to understanding how tactile and proprioceptive information is normally processed and why their absence is so limiting in prosthetic use.

Next, the focus shifts to current approaches for noninvasive sensory feedback in upper-limb prostheses, highlighting strategies such as transcutaneous electrical stimulation and mechanotactile interfaces that attempt to artificially restore part of this missing feedback.

Finally, the section introduces the concept of closed-loop myoelectric control, where sensory feedback is reintegrated into prosthetic systems to re-establish bidirectional communication between the device and the user. Together, these topics provide the theoretical basis for the feedback system proposed in this thesis.

2.1 The somatosensory system

The **somatosensory system** is a complex network of neural pathways and structures that processes sensory information from the body. It is composed of peripheral receptors and dedicated neural pathways that transduce environmental and internal stimuli to produce sensations of touch (mechanotransduction), temperature (thermoreception), pain (nociception) and body position (proprioception) [11].

In addition to basic somatosensory processing, the somatosensory system also includes higher-order networks responsible for various subfunctions such as haptic sensations and memory, body perception, body ownership, affective processing, and motor action [12].

2.1.1 Primary sensory neurons

The starting point of the somatosensory system is the **primary sensory neuron**, a specialized cell that receives external stimuli and transmits this information as electrical signals to the central nervous system for processing. They are the first neurons in sensory pathways that generate neural impulses to form our senses.

They are the basic unit of the somatosensory system, and they are also called **sensory receptor cells**. These are pseudo-unipolar cells whose axons bifurcate into two branches: one projecting toward the periphery and the other projecting toward the central nervous system (CNS). The cell bodies are located in ganglia on the dorsal root of the spinal or cranial nerve; while the peripheral terminals innervate the skin, muscles and joint capsules, where they contain specialized receptors that detect different types of stimuli. Figure 2.1(A) represents the cell bodies of somatosensory afferent fibers conveying information about the body. They reside in a series of dorsal root ganglia that lie along the spinal cord; and those conveying information about the head are found primarily in the trigeminal ganglia. Figure 2.1(B) shows a representation of pseudounipolar neurons in the dorsal root ganglia that give rise to peripheral processes that ramify within the skin (or muscles or joints) and central processes. These synapse with neurons located in the spinal cord and at higher levels of the nervous system. The peripheral processes of mechanoreceptor afferents are encapsulated by specialized receptor cells; while afferents carrying pain and temperature information terminate in the periphery as free endings.

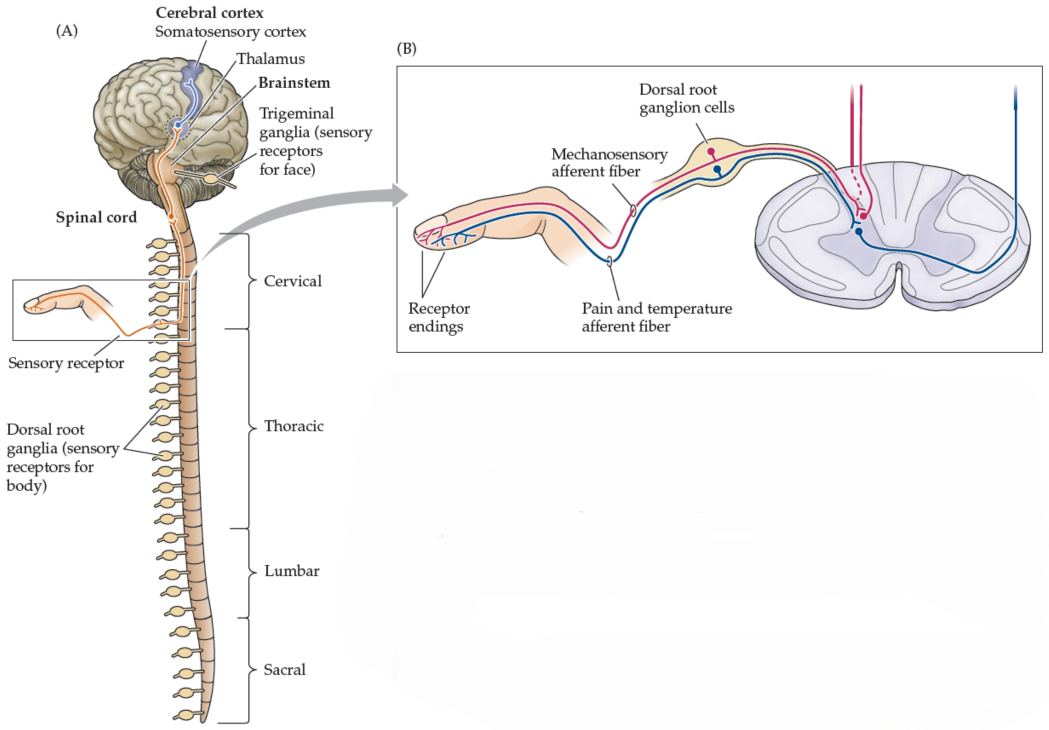


Figure 2.1: Somatosensory afferents convey information from the skin surface to central circuits.

Each somatosensory neuron can be subdivided into five functional zones, as seen in Figure 2.2:

1. The **receptive zone (1)** contains specialized receptor proteins that sense mechanical force, thermal events, or chemicals in the local environment and translate these signals into a local depolarization of the axonal terminals, called the receptor potential.
2. The **spike generation site (2)** is where the action potentials are generated, usually in the initial segment (distal to the first Ranvier node in the myelinated fibers).
3. The **peripheral nerve fiber (3)** is a long axonal projection that conducts the action potential from the sensory receptor toward the central nervous system. Its diameter and myelination determine conduction speed.
4. The **cell body (4)** is located in the dorsal root ganglion (for spinal nerves) or the cranial nerve ganglion, it houses the nucleus and metabolic machinery of the neuron.
5. The **spinal or cranial nerve (5)** is the gateway through which peripheral signals enter the central nervous system. It is a bundle of axons that carries the sensory information from the periphery into the spinal cord or brainstem.

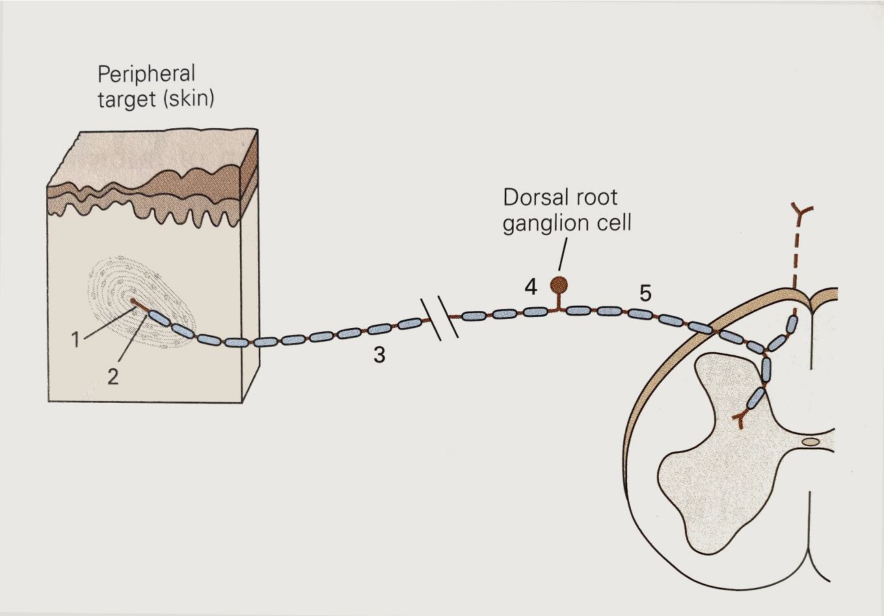


Figure 2.2: Somatosensory neurons functional zones. (1) The receptive zone. (2) The spike generation site. (3) The peripheral nerve fiber. (4) The cell body. (5) The spinal or cranial nerve.

Stimuli of sufficient strength produce **action potentials** that are **transmitted along** the **peripheral nerve fiber**, through the **cell body**, and into the **central branch** that **ends in the spinal cord or brain stem**.

While primary sensory neurons provide the interface between the environment and the nervous system, their ability to convey and transfer information depends on the properties of sensory afferents.

2.1.2 Sensory afferents

Sensory afferents are **nerve fibers** from sensory neurons that carry sensory information from receptors on the periphery of the body (like skin, muscles and organs) to the central nervous system (brain and spinal cord) [13].

The ability to sense the environment is a vital feature which allows us to detect and react to external cues. Somatosensation relies on sensory afferents being able to respond to a variety of both noxious and non-noxious triggers that signal discriminatory and/or painful events. They are a heterogeneous population of cells able to convey information related to distinct sensations such as touch, temperature, itch and pain [14].

Somatosensory afferents conduct action potentials at different rates, as they differ significantly in their response properties [15]. The **axon diameter**, the **size of the receptive field** and the **temporal adaptation** of their response to sensory stimulation, are key characteristics that differentiate these afferents.

For the development of this project, receptors in the fingers, hands and arms will be evaluated, with a focus on touch sensations such as contact and pressure. Understanding how these signals are transmitted requires first considering the **characteristics** of sensory fibers involved.

- **Axon diameter and conduction velocity:** most of the information subserving **touch** is conveyed by **Aβ afferents**. These are relatively large diameter fibers (6-12 µm) with a high conduction velocity (35-75 m/s). This rapid transmission is crucial for precise timing in tactile perception. It is important to mention that cutaneous mechanoreceptors (Meissner, Merkel, Pacinian and Ruffini cells) are a type of receptor that fall into this category, and they will be described in more detail in next Subsection 2.1.3.
- **Size of the receptive field:** for cutaneous afferents, the receptive field is the area of the skin surface over which stimulation results in a significant change in the rate of action potentials. The receptive fields in regions with dense innervation (such as fingers) are relatively small compared to those in the forearm or back that are innervated by a smaller number of afferent fibers. The size of the receptive field is largely a function of the branching characteristics of the afferent within the skin: smaller arborizations result in smaller receptive fields. This will give us insight into the spatial resolution in different regions, as seen in Figure 2.3. Different spike rates are sensed differently depending on the stimulus location, allowing spatial localization through differential neuronal activation. In the two-point discrimination test, represented in Figure 2.3, the

subject reports whether they perceive one or two points. **Fingertips** are areas with high density of mechanorecptors and small receptive fields, resulting in a low two-point discrimination threshold; meaning it is easy to distinguish two points even when they are very close together. In contrast, the **forearm** has lower density of mechanoreceptors and larger receptive fields, resulting in higher two-point discrimination threshold, meaning that the two points need to be farther apart to be perceived as separate. It is the minimum interstimulus distance required to perceive two simultaneously applied stimuli as distinct. Lowers thresholds indicate higher tactile acuity, with the fingertips and face being the most sensitive, while the forearm is better suited for detecting gross pressure or skin stretch (lower spatial resolution).

- **Temporal adaptation to stimulation:** sensory afferents are further differentiated by the temporal dynamics of their response to sensory stimulation. Slowly adapting afferents generate a sustained discharge in the presence of an ongoing stimulus. They provide information about the spatial attributes of the stimulus, such as size and shape and ca also detect stimuli associated with pain. On the other hand, Rapidly adapting afferents, fire rapidly when a stimulus is first presented and then fall silent in the presence of continued stimulation. They are articularly effective in conveying information about changes in ongoing stimulation such as those produced by stimulus movement.

Regarding the functional relevance to prosthetics, sensory afferent properties guide the choice of stimulation parameters in artificial feedback systems.

2.1.3 Mechanoreceptors: touch

Mechanoreceptors are afferent fiber terminals that detect and transmit tactile stimuli like contact, pressure, stroking, motion, vibration, itching or tingling. They are often encapsulated, enhancing sensitivity and selectivity, but can also be found as free nerve endings. The sense of touch can be understood as the combined result of the information provided by four systems working together: Meissner corpuscles, Merkel discs, Pacinian corpuscles and Ruffini corpuscles.

For the development of this Master's Thesis we will focus on the physiology and properties of **Meissner corpuscles**, **Merkel discs** and **Pacinian corpuscles**. Figure 2.4 summarizes their characteristics in a table. They are explained in detail, paying special attention to their role in the feedback application.

It is important to understand the functional properties of these mechanoreceptors to establish the appropriate stimulation parameters that can evoke realistic and intuitive tactile sensations. For example, choosing the right stimulation frequency requires knowing the specific frequency ranges to which these receptors are most sensitive. Although each mechanoreceptor has different activation characteristics, in a natural setting they are typically co-activated; thus, the

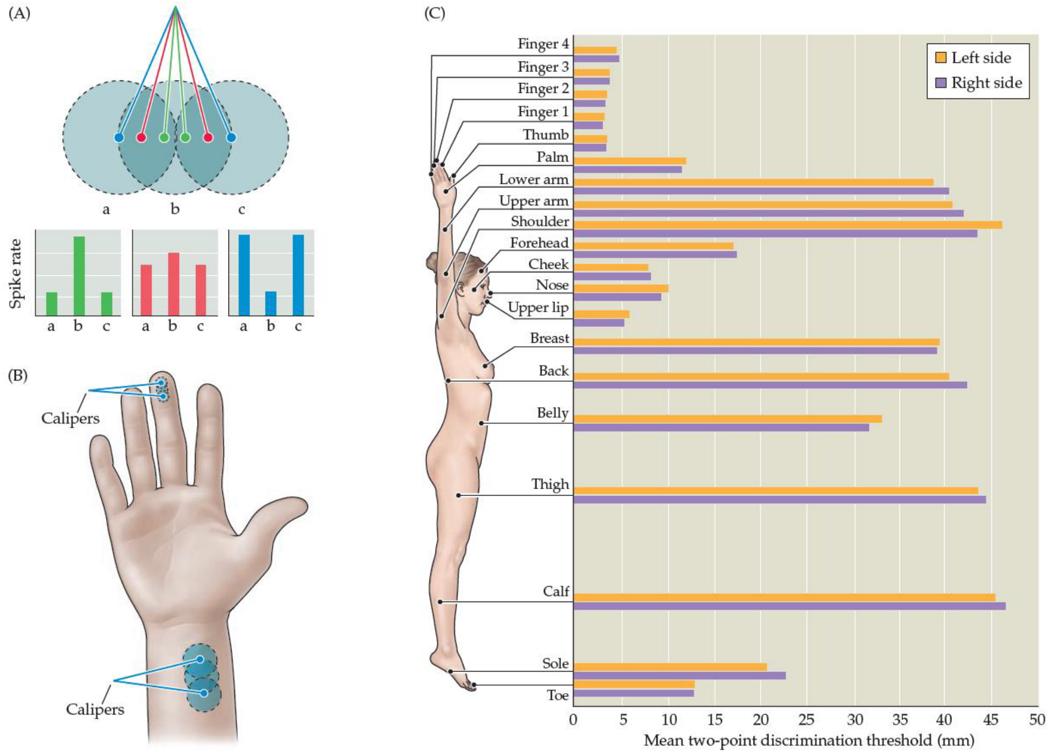


Figure 2.3: Two-point discrimination and somatosensory receptive fields across the body. (A) Schematic illustration of overlapping receptive fields in the skin (a, b, c) and the corresponding neural responses to localized stimuli. (B) Two-point discrimination is tested using calipers on the finger tip and forearm by applying simultaneous stimuli to the skin. (C) Mean two-point discrimination thresholds (in mm) measured on the left (orange) and right (purple) sides of various body regions.

user's perception results from their combined input rather than isolated activity of a single receptor type.

- **Meissner corpuscles** are considered a relevant physiological model for this project due to their implication in the detection of skin movement, motion and grip control: sensory functions and stimuli that are directly related to the tasks performed by an upper-limb prosthesis, such as adjusting grip force, detecting object slip, and interacting with textured or compliant surfaces. They are rapidly adapting mechanoreceptors, which means that they respond to dynamic stimuli and quickly adapt to constant pressure. They play a crucial role in sensorimotor control, helping us grasp and handle objects effectively, and they account for 40% of the mechanosensory afferents in the hand.
- **Merkel discs** account for approximately 25% of all mechanosensory afferents in the

human hand, and they are the only receptors situated directly in the epidermis, which places them in an ideal position to detect fine details of contact at the skin surface. One of the defining features is their exceptionally high spatial resolution, capable of resolving details on the order of 0.5 mm. This makes them the most precise of all cutaneous mechanoreceptors in terms of spatial discrimination. Functionally, they are highly sensitive to pressure, edges, points, and curvature, allowing them to play a crucial role in the perception of shape and texture. In addition, their slow adaptation properties mean that they can sustain their response during a prolonged stimulus, providing continuous information about the presence and form of objects in contact with the skin. Mimicking their response characteristics through carefully selected stimulation parameters, it becomes possible to provide prosthesis users with artificial feedback about stable grasping and handling small or delicate objects.

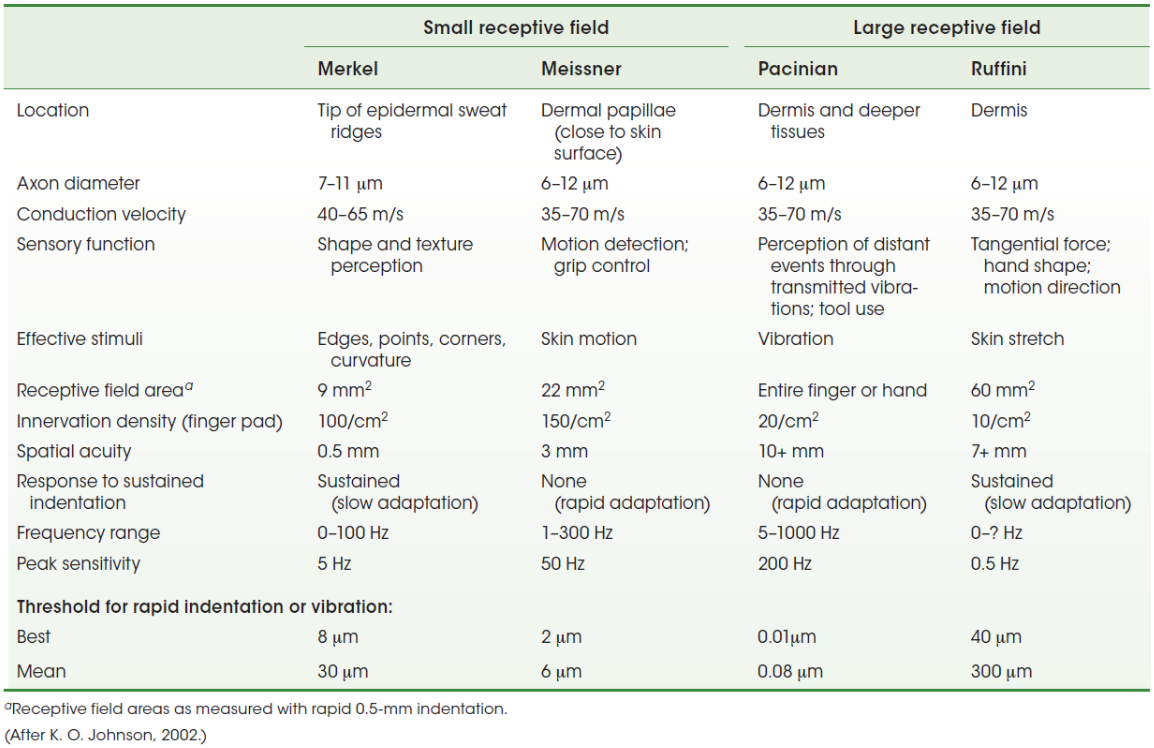
- **Pacinian corpuscles** are mechanoreceptors located deep within the dermis and subcutaneous tissue, innervated by rapidly adapting fibers. They represent about 10–15% of mechanosensory afferents in the hand. Although they have relatively low spatial resolution compared to other receptors, they are extremely sensitive to high-frequency vibrations, specialized for detecting transient events such as vibrations transmitted through objects during grasping, particularly at the moments of making or breaking contact. This property is fundamental for the skilled use of tools and for perceiving interactions with objects beyond the skin itself. By emulating these responses through electrical stimulation, the feedback system can deliver information about object interaction and grip stability.

2.1.4 Leminiscal pathway

The leminiscal pathway, also called dorsal column-medial lemniscus pathway, is an ascending sensory tract that transmits information from somatosensory receptors (cutaneous receptors and proprioceptors) to the spinal cord or brainstem, then to the thalamus (ventral posterior nucleus) and from there to the primary somatosensory cortex in the cerebral cortex. The somatosensory information on one side of the body is perceived by the primary somatosensory area on the contralateral side of the brain, as represented in Figure 2.5.

In the human nervous system the leminiscal pathway is responsible for transmitting fine touch, vibration and propioceptive information from the periphery (neck, trunk, limbs and the back of the head) to the brain. These types of somatosensory input are crucial for performing skilled, coordinated movements with the upper limbs, and forming an internal sense of body position and contact with the external environment.

In individuals with upper-limb amputation, this natural flow of somatosensory information is disrupted, especially when peripheral receptors and afferent fibers are lost. As a result,



	Small receptive field		Large receptive field	
	Merkel	**Meissner**	**Pacinian**	**Ruffini**
Location	Tip of epidermal sweat ridges	Dermal papillae (close to skin surface)	Dermis and deeper tissues	Dermis
Axon diameter	7–11 μm	6–12 μm	6–12 μm	6–12 μm
Conduction velocity	40–65 m/s	35–70 m/s	35–70 m/s	35–70 m/s
Sensory function	Shape and texture perception	Motion detection; grip control	Perception of distant events through transmitted vibrations; tool use	Tangential force; hand shape; motion direction
Effective stimuli	Edges, points, corners, curvature	Skin motion	Vibration	Skin stretch
Receptive field area[a]	9 mm^2	22 mm^2	Entire finger or hand	60 mm^2
Innervation density (finger pad)	100/cm^2	150/cm^2	20/cm^2	10/cm^2
Spatial acuity	0.5 mm	3 mm	10+ mm	7+ mm
Response to sustained indentation	Sustained (slow adaptation)	None (rapid adaptation)	None (rapid adaptation)	Sustained (slow adaptation)
Frequency range	0–100 Hz	1–300 Hz	5–1000 Hz	0–? Hz
Peak sensitivity	5 Hz	50 Hz	200 Hz	0.5 Hz
Threshold for rapid indentation or vibration:				
Best	8 μm	2 μm	0.01μm	40 μm
Mean	30 μm	6 μm	0.08 μm	300 μm

[a] Receptive field areas as measured with rapid 0.5-mm indentation.

(After K. O. Johnson, 2002.)

Figure 2.4: Afferent systems and their properties: comparison of the four main mechanoreceptors in the human hand.

prosthesis users often lack feedback on object contact, grip force, or limb position, which are essential for effective and intuitive motor control.

Closing the loop in myoelectric prosthetic systems by reintroducing artificial somatosensory feedback, through electrical stimulation of the skin over residual nerves or muscles, aims to reactivate parts of this lemniscal pathway. When surface electrical stimulation is applied over the median and ulnar nerve areas, it can evoke sensations that travel through surviving afferent pathways to the spinal cord and eventually up the lemniscal system to the somatosensory cortex. This strategy attempts to restore the natural sensory feedback that allows precise and adaptive motor behavior.

2.2 Noninvasive sensory feedback for upper extremity prosthesis

There are several approaches to delivering haptic sensation to upper extremity prosthetics using noninvasive sensory feedback, that is, transcutaneous electrical stimulation and mechanotactile stimulation. These are currently available approaches that do not involve surgery and can achieve high-level haptic displays, including tactile information, proprioception, and embodied ownership [16].

Kim et al.[17] developed a multifunctional haptic device, a tactor, that could deliver touch, pressure, vibration, shear force and temperature to the skin of an amputee of the upper extremity, especially in patients with targeted reinnervation. With this approach, patients could feel intuitive haptic feedback, allowing them to control their prosthetic hands for daily activities without training and additional cognitive effort activities.

In this project, electrical stimulation was chosen as the noninvasive feedback modality due to its flexibility, scalability, and ability to evoke reproducible tactile-like sensations through surface electrodes placed on residual muscles or nearby skin regions. **Transcutaneous electrical nerve stimulation** activates cutaneous afferent fibers, without causing muscular contraction, by delivering short low-amplitude current pulses, which the nervous system interprets as tactile feedback.

Adjusting the stimulation parameters, such as pulse frequency, amplitude, and duration, is possible to modulate the perceived intensity and quality of the sensation. These parameters are chosen to fall within the range of response of mechanoreceptors in the skin and transmit information about grip force or object stiffness.

However, to achieve intuitive haptic feedback, it is beneficial to satisfy two conditions **??**:

- **Somatotopic matching**: refers to the delivery of the artificial sensation to the same area of the body map in the brain (somatosensory cortex) where the natural sensation would normally be perceived, as each body region has its own representation (homunculus). In amputees, the challenge is that the natural skin area (the fingertips and hand) is no longer available, so direct somatotopic stimulation is impossible.
- **Modality matching**: refers to the reproduction of the same type of sensation (modality) that the original mechanoreceptor would have transmitted. Some examples of modalities are touch/pressure, vibration, shear force or temperature.

Non-hairy skin (such as fingertips, for example) is extremely sensitive, with spatial discrimination less than 1 mm and frequency response greater than 300 Hz. Current noninvasive methods (electrical or mechanical) cannot replicate that precision, so the brain must put in more cognitive effort to interpret the signals. In other words, the feedback does not feel as natural or automatic as real touch, so as a result, users must consciously interpret the artificial signals, increasing their cognitive load compared to the effortless perception of natural somatosensory feedback.

In transcutaneous electrical stimulation, it is difficult to achieve perfect somatotopic matching since stimulation is delivered on the residual limb, which means that sensations are typically felt there rather than on the phantom hand. However, with careful tuning of the stimulation parameters, it is possible to approach modality matching by evoking sensations such as pressure or vibration that correspond to prosthetic interactions. Although it is a less selective application, it is very little intrusive.

2.3 Closed-loop myoelectric control

A **closed-loop system** is a control system in which the output of an action is continuously monitored and fed back into the system to adjust future actions. In the context of myoelectric prosthetics, **feedforward** corresponds to the electrical signals generated by the user's muscles and sent to the prosthesis to produce movement, while **feedback** refers to the artificial sensory information delivered back to the user after the action [18]. Together, they establish a bidirectional communication pathway that enables more natural control of the prosthesis.

In an ideal case, an artificial replacement of the hand/arm should restore both motor and sensory functions by implementing a bidirectional communication between the system and the user's brain [9].

This concept lies at the core of Human-Computer Interfaces (HCI), in which human-generated patterns, in this case, muscular signals, can be categorized into different commands to control the activities of external devices, in this case, an arm or a hand prothesis. The loop is closed when the device does not only respond to user commands, but also provides meaningful sensory information back to the user [19].

The general components comprising the **control loop** are well defined:

1. The input interface providing command signals
2. The system to be controlled
3. The stimulation interface transmitting feedback information to the user

Different technologies are available to implement each of these components and there are multiple internal parameters that need to be adjusted depending on the application. It is important to bear in mind that in this Master's Thesis, a simplified closed-loop control system has been designed and implemented in a laboratory setting. The following decisions were made:

The **input interface** is responsible for capturing the user's intention and converting it into **command signals**. In the context of upper limb prostheses, the input interface is commonly implemented using electromyography (EMG) signals recorded from residual muscles. Myoelectric prostheses can be controlled using surface or intramuscular electrodes with a varying number of input channels: from a conventional two-channel interface to a high-density EMG [9].

Electroencephalography (EEG) is also one of the physiological signals frequently used in prosthetic device control techniques, especially in the upper extremities. However, the study of controlling prosthetic arms using brain signals is still in its early stages [1].

Having said this, the input interface providing command signals in this Master's Thesis is not explicitly defined because the goal is not to develop the feedforward branch of the loop, but rather the feedback one. In this setup, the robotic arm is used to simulate the behavior of a myoelectric prosthesis, allowing for testing of the feedback system in a controlled environment.

The **system to be controlled** refers to the prosthetic device itself, which performs the physical action. The controlled system may vary in mechanical complexity. It can range from basic grippers (e.g., Sensor Hand Speed by Otto Bock), to more advanced hands offering two or more grasp types (e.g., the Michelangelo Hand), or highly articulated systems with multiple degrees of freedom and individually controllable fingers (e.g., the Bebionic Hand or i-Limb).

In the laboratory, we count with several PhantomX Reactor Robots, a **robotic arm** equipped with a simple two-finger gripper that serves as the prosthetic device. This system can interact with objects of varying stiffness and apply different levels of force, simulating common grasping tasks that users would normally perform with his/her prosthesis.

The **feedback interface** delivers sensory information back to the user, allowing real-time adaptation and a sense of embodiment. This can be done through modalities such as vibrotactile stimulation, mechanotactile pressure, or electrical stimulation [16]. These modalities can be encoded through various parameters: intensity, frequency, or spatial distribution; depending on the information being conveyed.

In this Master's Thesis, a force sensor embedded in the robotic gripper measures the grasping force in real time. This data is then translated into a pattern of **electrical stimulation**, delivered to the user via an stimulator, explained in detail in Section 3.1.1. Stimulation is applied to the residual limb muscles of the arm through surface electrodes. The intensity of the stimulation is modulated according to the measured force, allowing the user to perceive how strongly the object is being gripped.

It is also important to mention that in each case, a specific configuration of the closed-loop system was selected based on the individual preferences of the authors and/or hardware availability.

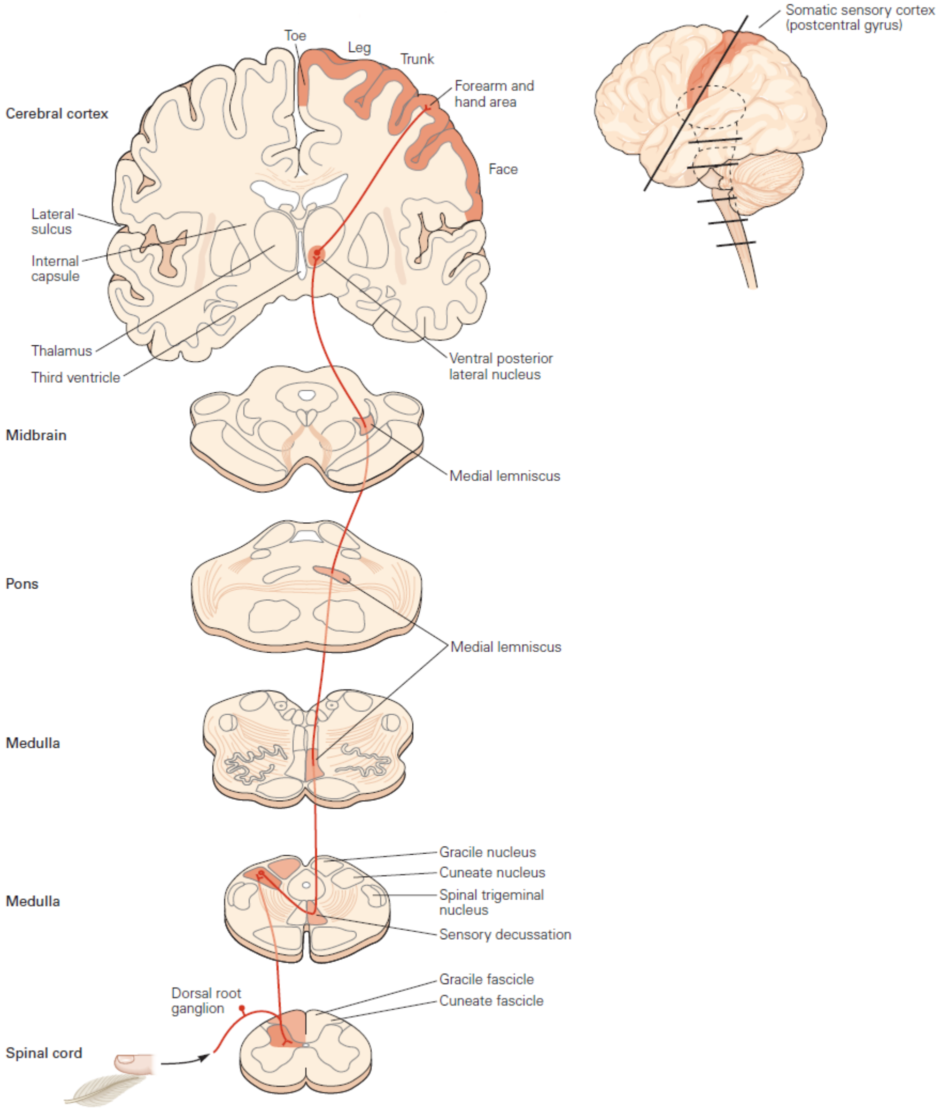


Figure 2.5: Ascending dorsal column-medial lemniscal pathway to primary sensory cortex. It is a major afferent pathway for somatosensory information that enters the central nervous system through the dorsal root ganglion cells. The flow of information ultimately leads to excitation of the somatosensory cortex

3. Development

This chapter describes the development of the experimental system designed to implement and test a closed-loop feedback strategy for upper-limb prostheses. The overall workflow can be summarized as follows: when the robotic gripper closes around an object, the force sensing resistor (FSR) detects the applied force. This signal is then processed and used to generate an electrical stimulation pattern through the EAST device, which is delivered non-invasively to the user's residual limb via surface electrodes. In this way, the user receives a sensation that is proportional to the stiffness of the object being grasped, partially **restoring the missing feedback loop** between action and perception. The following sections present the design of the system architecture, the integration of its main components (robot, sensor, stimulator, and control software), and the experimental procedures that were carried out to validate its performance.

3.1 Materials

In this section the different devices that constitute the feedback system will be explained, along with their purpose.

Figure 3.1 shows the role of each device in the feedback loop and how they communicate. An Arduino-based interface manages the acquisition of sensor data and communicates with the EAST stimulation unit. The Arduino board reads the resistance value from the FSR adjusted in the gripper of the robot. The signal is processed and the stimulation output is adjusted accordingly. MATLAB R2023a and the Arduino IDE are used for programming, signal processing, and coordination between components. This integration results in a synchronized sequence of events in which the prosthetic simulator (robotic arm) interacts with an object, the applied force is measured, and the corresponding electrical stimulation is delivered to the user in real time.

3.1.1 EAST device

The EAST (Electrical Afferent Stimulator for Tremor) device is an EMG amplifier and a voltage-controlled stimulator designed to deliver current pulses to target muscles or nerves through surface electrodes. In this Master's Thesis, the EAST device works as the *feedback interface* within the closed-loop control system, providing the user with somatosensory information. The EAST device was custom-made by OT Bioelettronica, in Torino, Italy [20].

In its standard operation, the EAST device allows for the adjustment of several stimulation

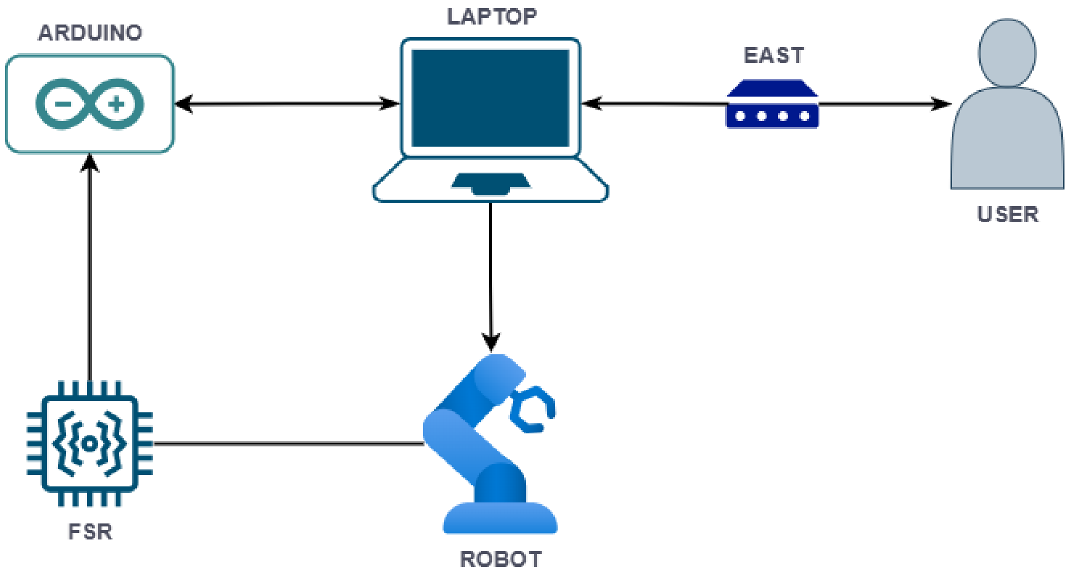


Figure 3.1: Architecture diagram of the general system flow

parameters, including **pulse frequency**, **pulse width**, and **output amplitude**. These parameters determine the quality, intensity, and perception of the evoked sensations in the patient. The device is connected to surface electrodes placed on the muscles of the residual limb of the user. By selectively activating cutaneous afferents and muscle fibers, the stimulation aims to elicit sensations that the user can interpret as related to the interaction of the prosthesis with objects.

Therefore, the EAST device receives real-time input signal that is proportional to the force measured by the Force Sensing Resistor (FSR) embedded in the robotic gripper. This mapping ensures that the stimulation intensity increases with the grasping force, allowing the user to perceive variations in grip strength and, consequently, the stiffness of the object being manipulated.

Using the EAST device allow the closing of the sensory feedback loop and restore part of the lost tactile and proprioceptive information in upper-limb prosthesis control. This enables intuitive, force-related feedback without requiring invasive procedures, making it suitable for preliminary testing in a laboratory environment.

The USB communication between the 16-channel device EAST and the PC uses a virtual COM implemented in the microcontroller. To start the communication between PC and EAST, a command string has to be sent through the USB port to configure the device and the communication protocol. These command strings allow the user to define the number of active channels, set the sampling frequency, adjust stimulation parameters, and optionally control data storage on the local SD card.

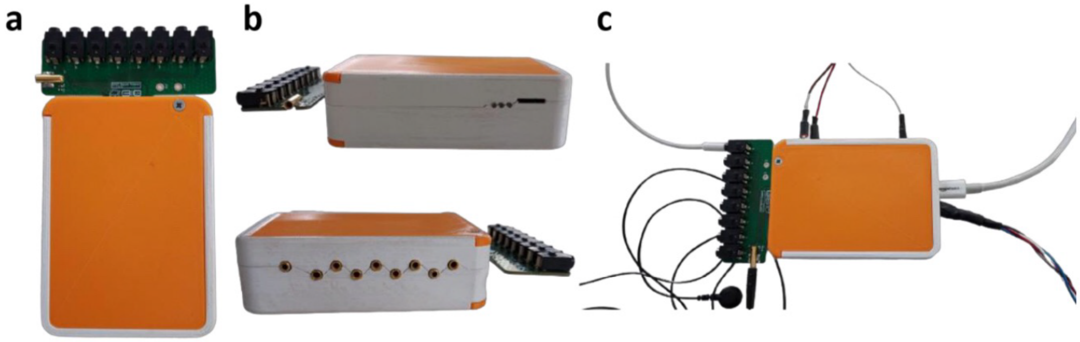


Figure 3.2: EAST device (a) top view, (b) side views and (c) complete setup.

The code managing this communication was developed in MATLAB, where specific command strings are used to switch the stimulation on or off with predetermined parameters such as amplitude (mA), frequency (Hz) and pulse duration (µs). Once activated, the stimulation remains constant until the device receives an instruction to stop or until the session duration ends.

The EAST device provides stimulation in discrete increments with a resolution of 0.5 mA. Internally, this is implemented as a vector ranging from 0.5 to 20 mA, with steps of 0.5 mA. Consequently, if the stimulation is set to 0 mA, the device defaults to the minimum available value of 0.5 mA. This corresponds to an output signal of 1 V, given that the EAST microcontroller was programmed assuming a fixed impedance of 2 kΩ, which serves as a simplified representation of human skin. However, it is important to note that the electrical properties of skin are more complex: the skin impedance is not purely resistive but depends on several factors, including hydration, electrode placement and geometry, and frequency [21]. Despite this, a purely resistive 2 kΩ model was deemed sufficient for the scope of the present work.

It is also relevant to note that the EAST device operates as a *tension generator*, even though communication with the user is defined in terms of current values. In other words, the device regulates voltage outputs that correspond to equivalent current levels under the assumed skin impedance. A true current generator would have been preferable, as it would guarantee a fixed current regardless of the actual impedance of the user, thus improving the precision of the stimulation. However, such an implementation would significantly increase the complexity and cost of the system. Therefore, the voltage-based approach of the EAST device represents a practical compromise that remains effective for the experimental validation of the proposed feedback system.

The EAST device plays a central role in this project as it serves as the stimulation interface of the closed-loop system. Its flexible configuration through MATLAB, adjustable stimulation parameters, and integration with the robotic gripper force sensor allow it to provide force-proportional feedback in a safe, noninvasive and controllable manner.

3.1.2 Force Sensitive Resistor (FSR)

Force Sensitive Resistor or Force Sensing Resistors (FSRs) are polymer thick film (PTF) devices that exhibit a decrease in resistance with an increase in the force applied to the active surface [22]. Its force sensitivity is optimized for use in human-touch control of electronic devices or force measurement, both in industrial applications and in medical devices. In addition, these sensors are flexible, lightweight, low-power and resistant. Depending on the application for which they are to be used, there are different shapes and sizes of resistive sensors.

FSRs offer significant advantages in terms of their low physical profile and cost-effectiveness (no need for bridge circuits or instrumentation amplifiers) [23]. However, they are not precision instruments for force measurement. They are rather useful for detecting trends or relative differences in applied force. Accuracy can vary from approximately ±5% to ±25%, depending on factors such as measurement consistency, sensor placement, and manufacturing tolerances, meaning that FSRs are more suited for qualitative assessments than for highly accurate quantitative measurements [22].

For optimal use and best results of the evaluation of the technology and the first implementation, it is important to choose the sensor that best fits the geometry of the application. Usually sensor size and shape are limiting parameters in FSR integration, so the sensor was picked to fit the mechanical actuation system, which is the PhantomX Reactor Robot gripper described in Section 3.1.3. Figure 3.3 shows the inner surface of this gripper with dimensions approximately of 4x3 cm, along with the FSR attached.

For this project, we decided to use the MD30-60 Flexible Pressure Sensor by Suzhou Leanstar electronics [24]. It is made from flexible nanofunctional materials with strong adhesion, bending resistance and high sensitivity. Its main characteristics are:

- Initial resistance: > 10 MΩ (Open circuit)
- Response time: < 1 ms
- Active area diameter: 25mm Ø.

On their own, FSRs are not pre-calibrated to correlate a force reading to a known engineering unit. However, the force measurement output captured can be correlated to the applied force through a calibration procedure [25].

When designing the actuation mechanism with the FSR, establishing a repeatable and reproducible system will provide a consistent force distribution, as the FSR response is very

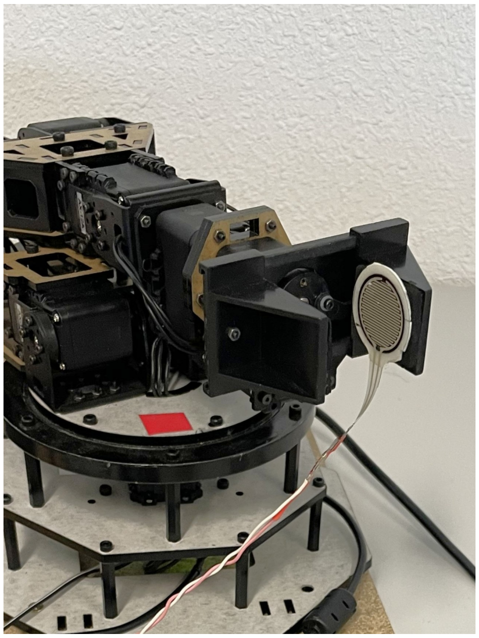


Figure 3.3: FSR fitted to the inner surface of the PhantomX Reactor Robot gripper.

Figure 3.4: MD30-60 Flexible Pressure Sensor by Leanstar electronics used in this project.

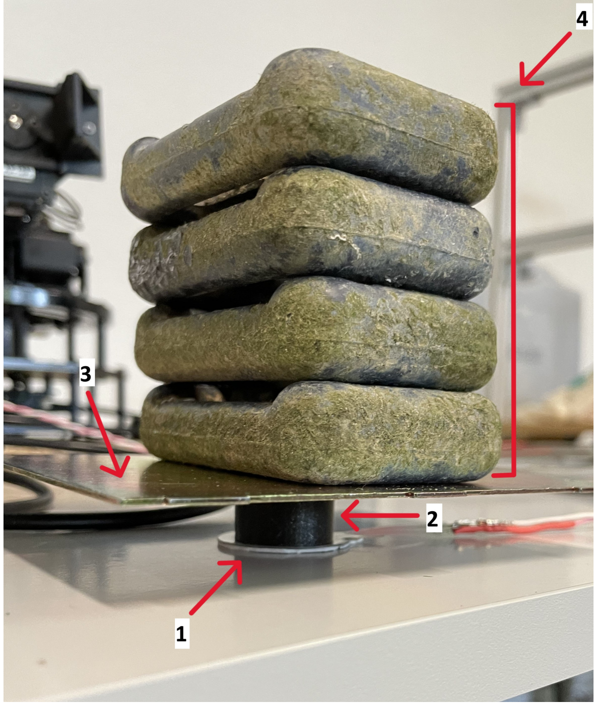


Figure 3.5: Know weights (4) were placed on a metalic platform (3) on top of the 3D printed disc (2) that distributes the weight around the sensor (1) in the flat surface

sensitive to the distribution of the applied force. In general, characterizing the sensors with dead weights is difficult. This is because the exact distribution of the weight on the sensor surface is rarely identical from one trial to the next. However, the use of an elastomer between the applied force and the FSR can help absorb the error of inconsistent force distributions, and as long as the distribution is the same cycle-to-cycle, repeatability will be maintained [22]. This is because the elastomer deforms under load and redistributes the applied force more evenly across the sensor surface, reducing the influence of localized pressure points. Thanks to its viscoelastic properties, it also acts as a buffer, smoothing out small variations in contact geometry.

To ensure accurate feedback of the system, a **sensor characterization procedure** was performed to establish the relationship between force ($F = m * a$) and the corresponding resistance output.

For that, the sensor was placed on a rigid, flat surface, and a custom-designed 3D-printed disc, matching the sensor's diameter of the active sensing area, was used to distribute the applied weight evenly across it. This element is represented in Figure 3.5 with the number 2. A series of tests were conducted in which known weights, represented in Figure 3.5 with the number 4, were placed on top of a metallic platform (number 3 in Figure 3.5) right above the 3D printed disc.

The test consisted of gradually increasing the mass applied to the sensor while recording the corresponding resistance. The collected data revealed a non-linear inverse relationship between the applied mass (or equivalent force) and the measured resistance. This curve, illustrated in Figure 3.6, can be approximated to a function as $y = ax^{-b}$.

The mass vs. resistance curve in Figure 3.6 provides an overview of the typical response behavior of the FSR. Force sensing resistors are a piezoresistive sensing technology. This means that they are passive elements that function as a variable resistor in an electrical circuit [26]. When no force is applied, the sensor has a very high resistance, typically in the order of megaohms (MΩ). As force increases, the resistance drops into the kiloohm (kΩ) range. At higher forces, the response starts to deviate from the expected power-law behavior. Eventually, the sensor saturates, reaching a point where further increases in force cause little or no additional decrease in resistance.

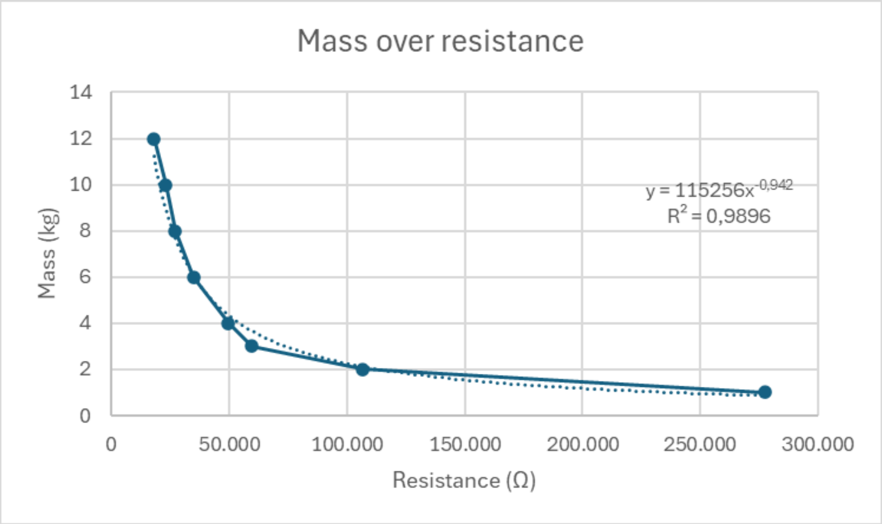


Figure 3.6: Mass vs. Resistance plot.

When considering the inverse of resistance (conductance), the conductance response as a function of force, is linear within the sensor's designated force range [22]. This can be seen in Figure 3.7.

Therefore, FSR sensors are sufficient and reliable to provide a good sensing modality, particularly for measuring force. In addition to being low-cost, FSR sensors are essentially very useful devices that are able to provide good active compliance control, particularly for the grasping robotic hand [27].

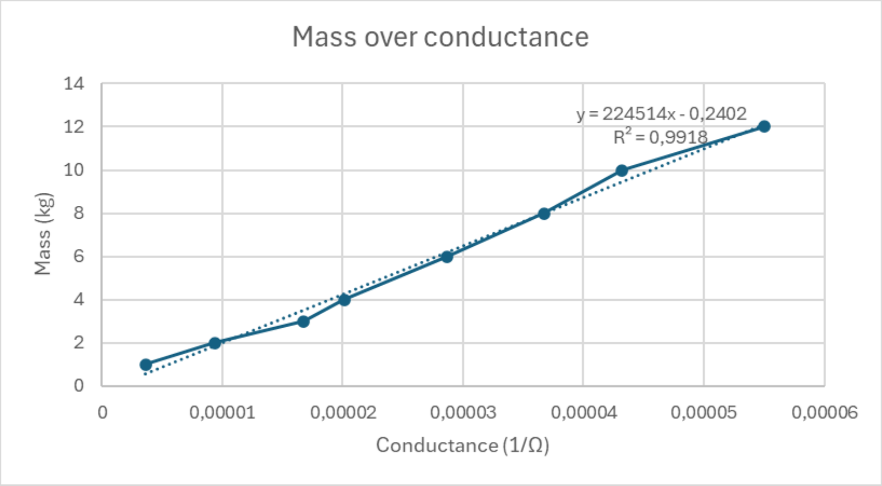


Figure 3.7: Mass vs. Conductance plot.

3.1.3 PhantomX Reactor Robot

The PhantomX Reactor Robot Arm, developed by Interbotix Labs (Trossen Robotics), is a research-grade robotic manipulator designed for versatility, precision, and affordability, and is well-suited for educational and university-level research environments [28]. It is shown in Figure 3.8. It features a compact, yet robust design and integrates high-performance Dynamixel AX-12A actuators for joint motion and feedback.

The arm comprises five degrees of freedom (DoF), and its structure is built from durable materials such as Delrin, acrylic, and metal that ensure both stability and precision during movement [28].

In the context of this Thesis, the PhantomX Reactor serves as a **prosthetic simulator**, emulating the motor capabilities of a myoelectric or EEG-controlled upper-limb prosthesis. Although the robot has multiple joints, only the **gripper mechanism** is used. Two advantages of using this robot are that 1) I am already familiar with its functioning, as it was used in laboratories during the master's degree; and 2) the gripper aperture is adjustable, allowing for a fully customizable experiment.

Functionally, the gripper simulates the action of the fingers grasping an object, allowing controlled experiments measuring timing, closing velocity, and force application. This setup facilitates precise synchronization within the feedback system.

Regarding technical specifications, the gripper has a rated holding strength of up to 500 g, while the wrist itself can lift up to 250 g horizontally (150 g if using the wrist rotation) [28].

The Reactor arm is equipped with a microcontroller and offers flexible control options in-

Figure 3.8: PhantomX Reactor Robot used to mimic the functionality of an upper-limb prosthesis

cluding Arduino IDE compatibility and USB, as well as analog and digital I/O ports. It is also ROS-ready, supporting integration into robotic software ecosystems for advanced control applications.

3.2 Methodology

This section describes the strategy and procedures followed for the development and validation of the proposed sensory feedback system. It defines how the different components interact, how they are configured, integrated and tested; and the workflow since the force is captured until the patient receives the feedback.

First, the overall architecture of the system is introduced, including the components presented in Section 3.1. Then, a control framework is presented as the software and hardware layer that manages the interaction between components of the system. It comprehends all the circuitry and electronics, but also the functions and code necessary for its function. The integration of Arduino and MATLAB environments for signal acquisition, processing, and device communication is also included. The operation and configuration of the EAST stimulation device are detailed, highlighting its role as the feedback interface. Finally, the experimental setup designed to evaluate the performance of the system in a controlled laboratory environment is outlined.

3.2.1 Stimulation protocol

The EAST device sends a 100 Hz, 400 µs duration, bifasic pulse, with variable amplitude (mA). This is the stimulation signal that will reach the user's arm for feedback sensation, through 1 electrode placed on the median, ulnar or radial nerves (red) and 1 electrode on the elbow as ground (black), due to the thin skin and bony structure. This setup is shown in Figure 3.10a. This electrode placement was selected to maximize the likelihood of stimulating afferent fibers belonging to the leminiscal pathway, originally projected to the hand and fingers, thereby increasing the intuitiveness of the feedback.

The sensory innervation of the hand is mainly provided by the **median**, **ulnar**, and **radial nerves**, as shown in Figure 3.9. Together, they transmit the majority of tactile and proprioceptive information from the upper limb to the central nervous system.

These **median and ulnar nerves** account for the majority of the palmar innervation, areas of the hand most engaged in grasping and manipulation, which are particularly interesting for this Master's Thesis. The **median nerve** is responsible for innervating the palmar side of the thumb, index, middle finger, and the radial half of the ring finger. For this reason, it is of particular interest when attempting to restore sensory function through electrical stimulation. The **ulnar nerve** innervates the little finger and the ulnar half of the ring finger, as well as the corresponding palmar and dorsal areas.

The **radial nerve** primarily provides sensory innervation to the dorsal surface of the hand. Although its contribution to palmar tactile sensation is limited, it can be relevant for the perception of contact and proprioceptive information during certain grasping and release movements.

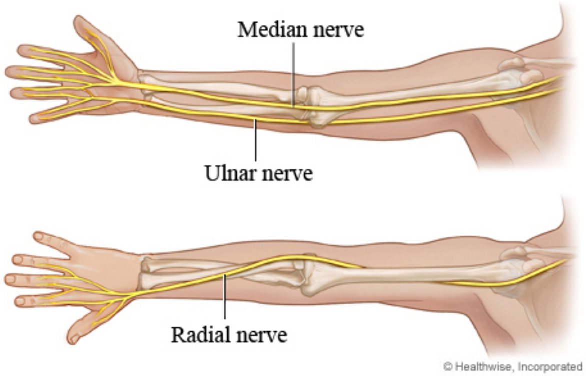
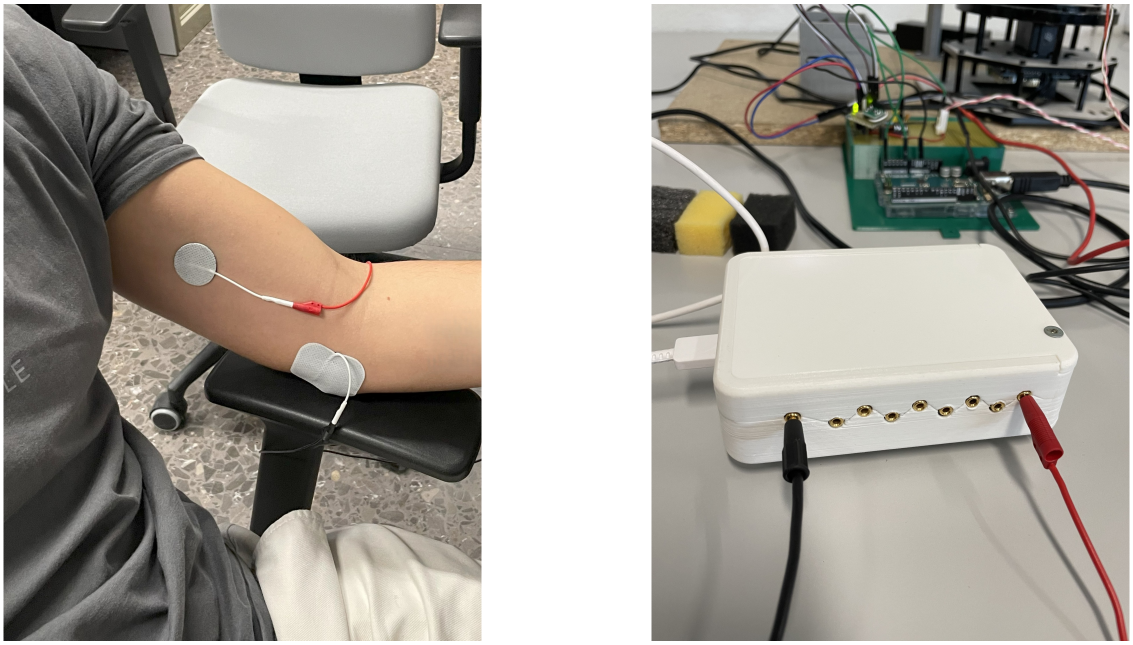


Figure 3.9: Sensory innervation of the hand by the median, ulnar and radial nerves.

When electrical stimulation is implemented, different waveform configurations can be used. In this project, the EAST device generates a **biphasic pulse train** consisting of two consecutive phases of opposite polarity, ensuring that the net charge at the electrode–skin interface is



(a) Electrode setup for stimulation. The rounded electrode is placed on the median, ulnar or radial nerve with the red banana cable and the squared electrode is placed on the elbow bone with the black banana cable

(b) Red banana cable connected to channel 1 for stimulation and black banana cable connected to the EAST reference.

Figure 3.10: Electrodes setup for stimulation and cable placement in EAST.

close to zero. This signal is shown in Figure 3.11, captured in an oscilloscope in the lab. This prevents charge build-up and avoids causing discomfort or even skin irritation due to electrochemical reactions. We can say that biphasic pulses are considered more comfortable for prolonged or repeated sensory feedback applications.

The chosen stimulation frequency of 100 Hz lies within the responsive range of the cutaneous mechanoreceptors (particularly the Meissner and Pacinian corpuscles), which are known to encode pressure sensations in this range, as well as grip control and vibrations. The pulse width of 400 μs is consistent with the values commonly used in neurological applications, providing effective recruitment of afferent fibers while minimizing discomfort [29]. This will allow for a reliable evocation of tactile sensations. Finally, the amplitude of the stimulation in mA is dynamically modulated according to the grip force measured by the force sensor, creating an intuitive mapping between the prosthetic interaction with objects and the feedback perceived by the user.

It is very important to mention that the amplitude range of the stimulation pulses must be individually adjusted for each patient at the beginning of each experiment. This is because every participant has a different level of sensitivity: their nerves may have been affected by

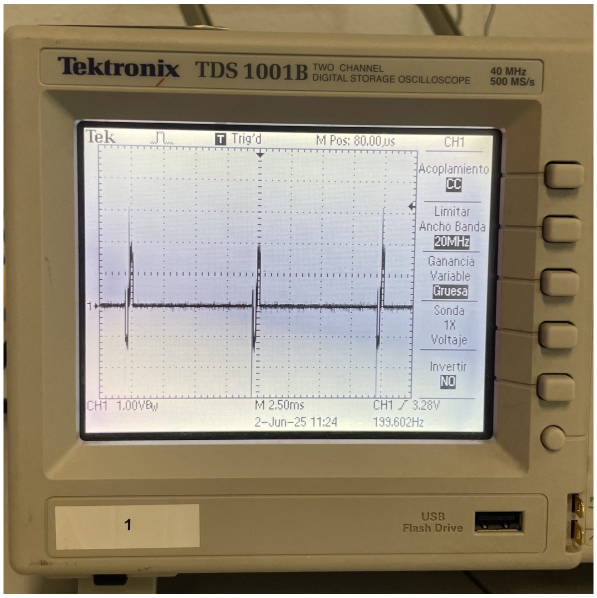


Figure 3.11: Biphasic signal generated by the EAST device to stimulate at 100 Hz with 400 µs pulse duration

the amputation, or they may simply exhibit different perceptual and pain thresholds. In this application, the stimulation range was set between a minimum perceptible intensity of 2 mA and a maximum of 6 mA, which remains safely below the motor activation threshold. The aim is to evoke clear and perceptible sensations while avoiding muscle contractions.

In a study exploring novel strategies based on sensory electrical stimulation for the management of tremor in Parkinson's disease, the EAST device was used to evaluate the therapeutic effect of afferent stimulation on the reduction of tremor [30]. Although the stimulation paradigm in that work was not intended for feedback or closed-loop prosthetic applications, the stimulation parameters were comparable in terms of frequency and pulse duration. However, because the goal was to induce reflexive and inhibitory effects, the amplitudes used were substantially higher. Although the EAST device is limited to a maximum of 20 mA, the study reported stimulation intensities of the order of tens of milliamperes. This contrast highlights that, although the present project addresses a completely different application, the stimulation amplitudes selected for feedback delivery in prosthetic users remain conservative, prioritizing both safety and comfort of the participants.

It is also worth noting that the stimulation parameters: frequency, pulse duration, and amplitude, can be combined in numerous ways, each potentially leading to different perceptual qualities and levels of effectiveness. The systematic exploration of these combinations and their impact on the type and quality of sensations evoked represents a research field of its own. In fact, a comprehensive analysis of how the sets of varying parameters influence user comfort, perceptual discrimination, and functional outcomes could form the basis of an entirely separate project, extending beyond the scope of the present work.

3.2.2 Control framework

The control framework refers to the software and hardware system that manages the interaction between the components of the feedback system. The stimulation signal parameters, previously stated in Section 3.2.1, make the pulse of the signal very short, making it difficult to detect or capture the peaks. To solve this, an electronic system was designed and implemented in an Arduino UNO board.

The electronic and hardware part of the project can be divided into 2 main systems:

1. The part of the system containing the **FSR** is an independent circuit that is a **tension divisor**, illustrated in Figure 3.12.
2. The part of the system that handles the **stimulation of the EAST device** is a **reading circuit** that detects the peaks of the output signal to plot it. The general ideas of this circuit, represented in Figure 3.13, are:
    - **Muscle stimulation**: monitor what the EAST device is actually delivering without interfering with the stimulation of the patient.
    - **Processing for visualization**: the goal is to convert a very fast biphasic pulse into a slow signal that the Arduino ADC can measure.

   The ultimate goal is to compare the signal with the force detected by the sensor.

The peak detector diagram in Figure 3.13 is a custom circuit designed and implemented to monitor and plot the stimulation pulses generated by the EAST device, and to make them accessible for acquisition by the Arduino's analog-to-digital converter (ADC). The Arduino ADC converts incoming analog voltages into digital values (with a 10-bit resolution over a 0–5 V input range), enabling the microcontroller to record and process them. Since the raw biphasic stimulation pulses are very short and change too quickly to be captured directly at this resolution, the custom circuit adapts them into a slower, smoothed signal that the Arduino can reliably sample. The goal of this circuit is to obtain a reliable representation of the stimulation amplitude actually delivered to the electrodes by adapting the fast biphasic pulses generated by the stimulator into a form that could be captured within the sampling limitations of the Arduino.

The **EAST device** delivers biphasic pulses through the positive electrode of the generator, placed on the muscle of the patient, and the reference electrode is connected to the ground of the reading circuit. In this configuration, the body acts as a **resistive load** with a skin

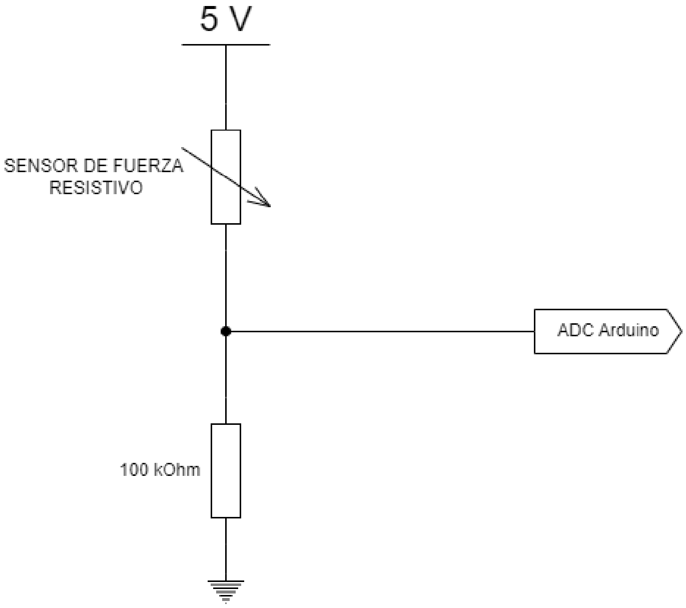


Figure 3.12: Force sensor diagram

impedance of approximately **2 kΩ**. The current, which is the magnitude that provokes the physiological response in our body, flows towards the circuit to capture and plot it.

To estimate the current reaching the skin, a **47 Ω resistor** was included in series into the mesh, as seen in Figure 3.13. Because the value of this resistor is so low compared to the skin impedance (2 kΩ), the stimulation reaching the participant remains practically unchanged, while the current that flows through it can be used to measure the voltage drop across the resistor. In this way, the reading circuit does not affect the stimulation value sent from the EAST, which only depends on the transference function defined in Figure 3.14, and the voltage value read from the force sensor.

The **operational amplifier** in Figure 3.13 is configured as a buffer to **isolate** the measurement branch from the stimulation circuit by copying the voltage from the non-inverting pin to the output, without allowing current to pass. It is powered with a dual ±5 V supply, which allows to handle signals both above and below 0 V and provides sufficient headroom for the output to reproduce the incoming waveform without distortion. The inverting pin of the op-amp receives feedback from the output through the **100 kΩ resistor** and is referenced to ground through the **10 kΩ resistor**. This results in a non-inverting **amplification** with a gain of approximately $G = 1 + (100k/10k) = 11$. This amplification will convert the small voltage drop at the 47 Ω resistor in a value close to the usable range of the ADC (0–5 V).

Between the op-amp output and the measurement node, a **1N4148 diode** is placed, as seen in Figure 3.13. Importantly, this diode is included inside the feedback loop of the op-amp,

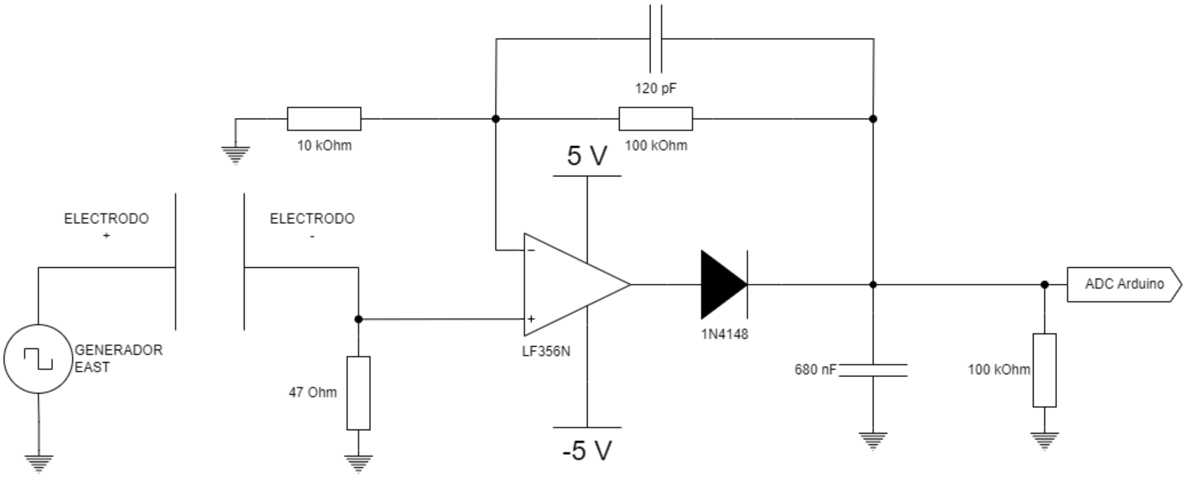


Figure 3.13: Peak detector diagram

configuration known as a **rectifier**. This will only allow the positive part of the signal to pass through towards the measurement node. At the same time, the op-amp compensates for the forward voltage drop of the diode, ensuring that the rectified signal retains the full amplitude of the input without the usual 0.7 V loss. To stabilize the circuit, a small **120 pF capacitor** is connected in parallel with the 100 kΩ feedback resistor to smooth high-frequency components and improve stability by preventing potential oscillations in the op-amp.

After the rectification stage, the signal is passed to a **peak detection circuit** composed of a **680 nF capacitor** and a **100 kΩ resistor** connected to ground, as seen in Figure 3.13. When a stimulation pulse arrives, the capacitor charges to the peak voltage, acting like a bucket, and the diode prevents it from discharging immediately. The parallel resistor of 100 kΩ, acting like a drain, allows the capacitor to discharge gradually, extending the time window over which the Arduino can read the voltage. In this way, short stimulation spikes are converted into slowly decaying signals, preserving their peak information while matching the Arduino's acquisition speed.

The discharge rate is defined by the RC time constant $\tau = R * C = 100kW * 680nF = 68ms$, which means that the envelope takes approximately 68 ms to decay. Since the stimulation pulses are delivered at 100 Hz (every 10 ms), the capacitor does not fully discharge between pulses. As a result, the Arduino does not measure the original fast biphasic waveform, but instead a slowly varying envelope that reflects the amplitude of the stimulation peaks. It is important to note that the choice of the time constant represents a trade-off. If τ is too large, the envelope may not decrease sufficiently before the next pulse, reducing temporal resolution. Conversely, if τ is too small, the capacitor discharges too quickly, and the Arduino may fail to register the peak correctly. The selected value provides a suitable compromise for reliable peak detection while maintaining responsiveness.

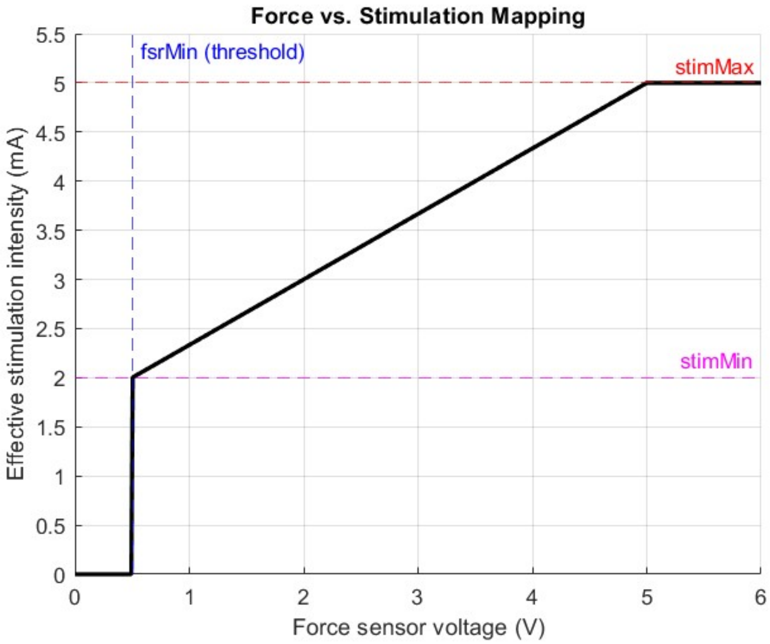


Figure 3.14: Transfer function that maps the voltage read in the sensor to the corresponding amperage in mA of effective stimulation

Finally, the conditioned signal is directed to the Arduino analog input, and then, transmitted to MATLAB, where custom functions (e.g., readStimulation) were programmed to process and display the stimulation waveform. The code developed for this Master's Thesis for the configuration, reading and processing of the signals, can be found in Annex C, where the corresponding link is provided. The obtained result is represented in Figure 3.15. This integration allows to directly monitor the stimulation values being delivered during each trial, ensuring that the system behaves as intended and that the safety and comfort thresholds for the participant are respected.

The image on the left in Figure 3.15, the voltage output of the Force Sensing Resistor (FSR) during a manual squeezing task is shown. As pressure on the sensor increases, the resistance decreases, resulting in a progressive rise in the measured voltage. This signal reflects the force applied to the gripper.

On the right, the corresponding stimulation voltage delivered to the user is plotted. This signal depends directly on the FSR voltage and thus represents the feedback delivered through the EAST device. As the FSR reading increases, the stimulation intensity rises accordingly, allowing the user to perceive a stronger sensation in the arm. During the experiment, this effect could be felt directly: squeezing the sensor caused a gradual increase in stimulation intensity, making the feedback intuitive and proportional to the applied force.

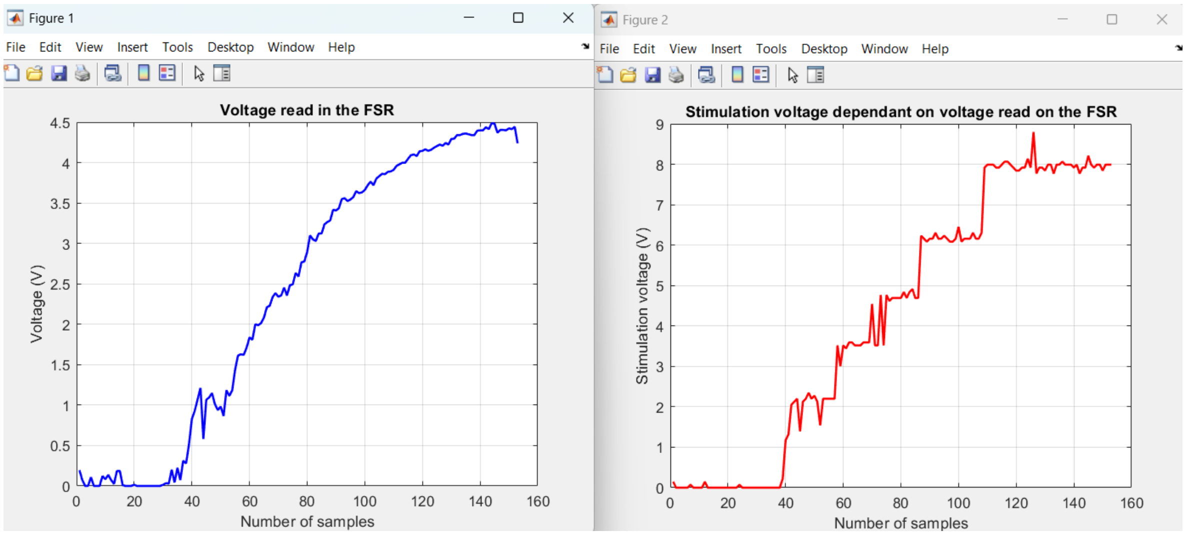


Figure 3.15: On the left, the representation of the force read in the FSR as voltage. On the right, the output of the reading circuit, representing the stimulation voltage dependent on the voltage read in the FSR

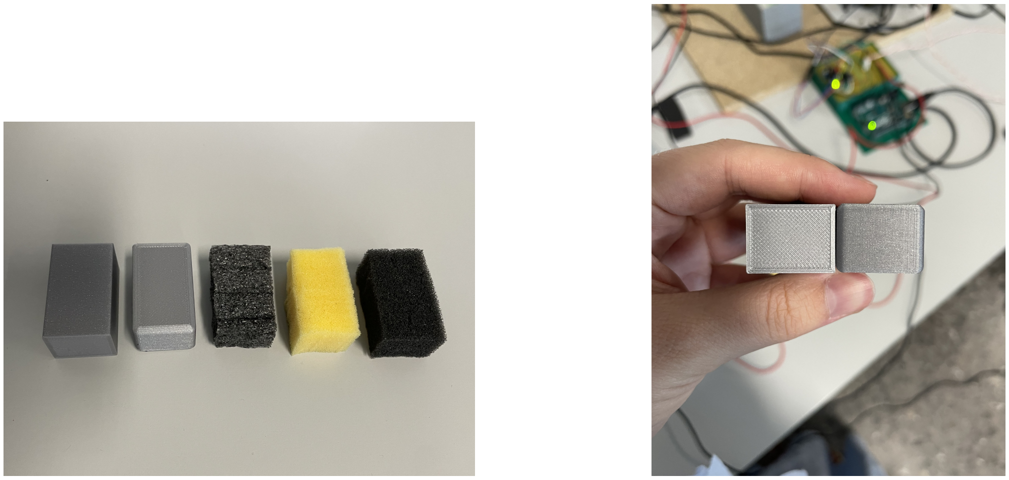
Interestingly, it can be seen in Figure 3.15 that the stimulation signal shows a *staggered, step-like pattern*. As previously mentioned in Section 3.1.1, this behavior originates from the programming of the EAST device, which delivers stimulation in discrete increments of 0.5 mA. Consequently, even though the FSR produces a continuous signal, the feedback to the user is quantized, creating the staircase-like appearance in the stimulation curve.

From a perceptual point of view, this quantization may result in the user experiencing small "jumps" in stimulation intensity rather than a perfectly smooth, continuous change. While this effect does not compromise the overall function of the system, it highlights an important limitation of the current setup: the resolution of the stimulator may influence the naturalness and subtlety of the feedback.

3.2.3 Experimental setup

To evaluate the proposed feedback system, an experimental setup was designed to test the response of the force sensing resistor when interacting with **objects of different stiffness levels**, and to assess how this response could be translated into electrical stimulation feedback for the user. The experiment combined custom-made test objects, a robotic platform acting as a prosthetic simulator, and the EAST stimulation device integrated with the control architecture.

For the test objects, rectangular blocks of identical size and thickness with different mechanical



(a) Blocks used to test different stiffness from softer (on the right) to rigid (on the left)

(b) Cross-section of version 1 and 2 of the 3d printed rigid block

Figure 3.16: Rectangular blocks of same size and thickness with different mechanical properties used for Experiments 1 and 2

properties were used, as seen in Figure 3.16 (a) and (b). Three blocks were cut from foams of varying densities to simulate softer materials, and a rigid block was created using 3D printing to represent a hard object. The first version was printed with straight edges, which caused localized indentation of the force sensor and prevented uniform contact across the surface, as it is flexible. To address this issue, a second version with rounded edges and corners was produced, which ensured full and consistent contact with the sensing area. The two versions of the 3D-printed blocks are shown in Figure 3.16 (b).

The laboratory setup involved preparing the system architecture by connecting the PhantomX Reactor robotic arm to the power supply and the PC, along with the EAST device and the Arduino board. Before placing the electrodes on the arm, the **participant's skin** was carefully **cleaned** with **alcohol** to remove oils or residues that could interfere with signal transmission. One stimulation electrodes from the EAST device were positioned over muscles embedding the neural pathways of the median, ulnar, and radial nerves at different levels of the arm (depending on the type of amputation: transhumeral, transradial, etc.), with a reference electrode placed at the elbow, as seen in Figure 3.10 (a).

The general pipeline consisted of closing the robotic gripper around the different test blocks, recording the force detected by the FSR and applying the corresponding stimulation through the EAST device. For this, **3 experiments** were designed to collect all relevant data for the subsequent analysis of perception of patients of the different levels of stiffness.

- **Experiment 0**: a basic configuration was tested before gluing the sensor to the robot gripper, in which the stimulation is programmed as a simple lineal mapping dependent on the force read in the sensor. The FSR in this experiment was still on the protoboard, as seen in Figure 3.17. This experiment allowed us to check the sensation of the stimulation when human fingers pinched the sensor, this way we could practice how hard we would grab objects and adjust our strength to feel different intensities.

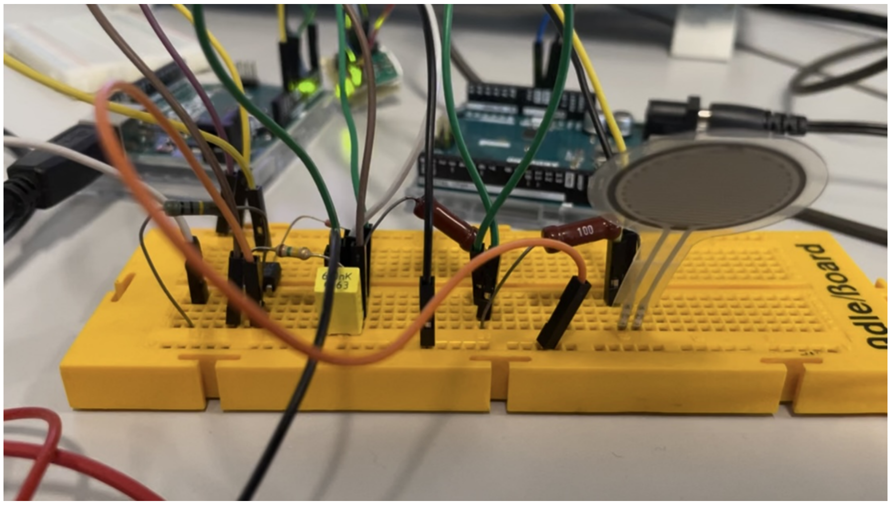


Figure 3.17: Experiment 0 setup.

- **Experiment 1**: in this experiment the robot was incorporated into the loop, as seen in Figure 3.18. The force sensor is placed on one side of the gripper. The different prepared materials are positioned between its claws to test how they elicit different stimulation levels. This experiment will reveal information about the relationship between the **materials**, the **level of closure of the gripper**, which will translate into the strength in which the prosthetic device will grab, and the **stimulation intensity**. The movement of the robot gripper was programmed in the Arduino IDE because the gripper openness can be modulated.
  - **Material profiling:** before analyzing any stimulation, the voltage read in the FSR was recorded for each material. The gripper was commanded to close at three distinct opening levels, providing raw data on how the sensor responded to different stiffness conditions. This generated four graphs (one per material), each displaying the sensor's output for the three gripper openings. They can be found in Figure 4.2.
  - **Gripper opening profiling:** in a similar way, for each gripper opening, each of the materials were grasped at a certain level of closure. Here, the result will be grouped by aperture level, in order to compare how for a certain closure strength, different materials will elicit different voltages.
- **Experiment 2**: after characterizing the raw responses both, by material, and by aperture level of the robot gripper in the Experiment 1, the same gripper apertures were

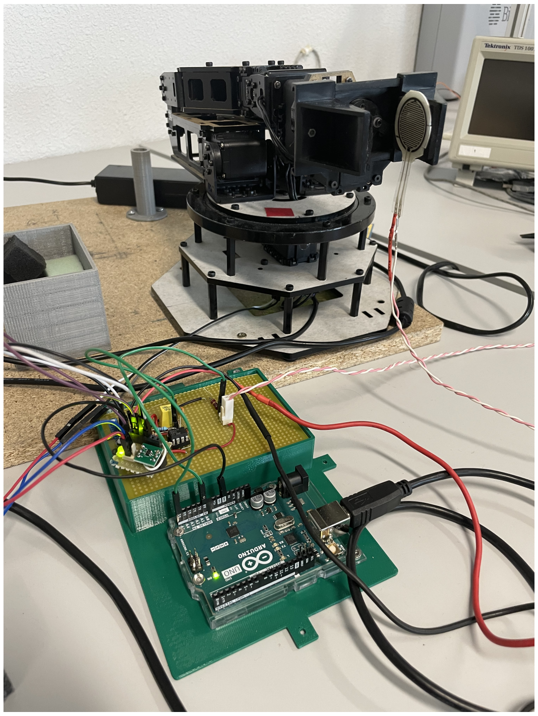


Figure 3.18: Setup for experiments 1 and 2, that include the robot, the FSR attached to its gripper and the circuitry necessary for the reading of the stimulation signal.

executed again, but this time with the **stimulation system fully integrated in a subject**. The recorded force signals for the different materials were used to drive the EAST device, producing proportional stimulation in real time. This setup allowed us to analyze how the discrete force patterns obtained from the different materials translated into electrical feedback signals, and ultimately how these differences could be perceived by the user.

The ultimate goal of this experimental design is to explore whether users can differentiate the stiffness of objects through the **electrical feedback delivered to their muscles**, thereby testing the feasibility of the proposed closed-loop system.

The results of these experiments can be found in Section 4.

4. Results

This section presents the experimental results obtained from the evaluation and validation of the proposed feedback system. The final aim of the experiments was to assess how the force sensing resistor (FSR) embedded in the robotic gripper responded to objects of different stiffness levels, and how this information could be translated into electrical stimulation through the EAST device.

Three experiments were conducted to validate the feedback system. Experiment 0 tested a simple mapping of force to stimulation using the FSR on a prototyping board, allowing initial validation with finger pinching. Experiment 1 integrated the FSR into the robotic gripper to characterize responses of materials with different stiffness levels at various gripper apertures. Finally, Experiment 2 combined these responses with real-time stimulation on a subject, assessing whether material stiffness could be distinguished through electrical feedback.

4.1 Experiment 0: Preliminary validation with direct sensor manipulation

In this first experiment, the FSR was not yet integrated into the robotic gripper, but remained on the proto-board. A simple linear mapping was programmed to directly convert the force values detected by the sensor into proportional stimulation commands for the EAST device. By pinching the FSR with the fingers, it was possible to experience first-hand how changes in applied force translated into varying stimulation intensities.

Figure 4.1 shows the force ejected by a user when pinching the sensor (on the left) and the consequent stimulation they received from the EAST device (on the right). This trial served two purposes: (i) to validate the correct operation of the signal acquisition–stimulation pipeline, and (ii) to provide intuitive feedback about the sensitivity of the stimulation to force increments. Users could learn how hard to press in order to feel different intensities, which set the basis for the integration of the system in the robotic platform.

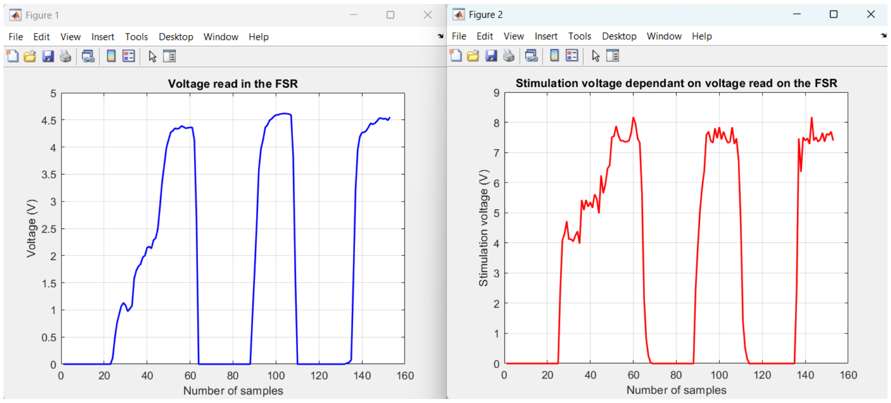


Figure 4.1: Comparison side by side of the force detected by the FSR (left) and stimulation sent from the EAST, dependent on that force (right).

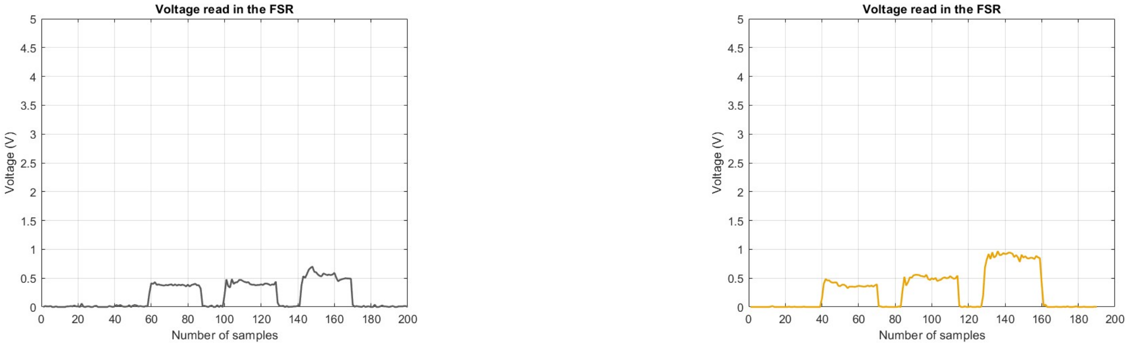
4.2 Experiment 1: Force sensor characterization with robotic gripper

In this stage, the FSR was mounted inside the gripper of the PhantomX Reactor robotic arm. The aim was to characterize how the sensor responded to objects of different stiffness levels when grasped under controlled gripper apertures. Two complementary analyses were performed:

4.2.1 Material profiling

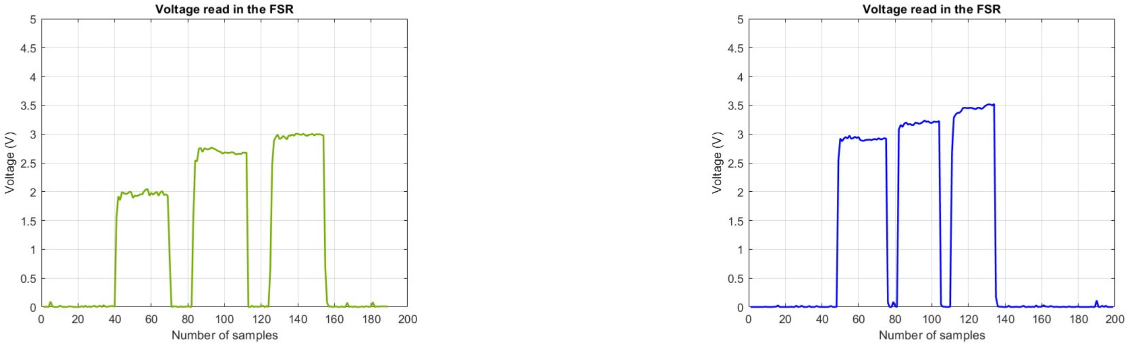
The first analysis focused on the sensor response across the different materials shown in Figure 3.16. Each of the prepared blocks (three foams of different densities and one rigid 3D-printed block) was individually grasped by the robotic gripper. The gripper was commanded to close at three predefined aperture levels, which correspond to the position values used in the Arduino control program. An aperture level of 220 corresponds to a small closure (gripper almost open), 180 corresponds to a medium closure, and 140 corresponds to a large closure (gripper more tightly closed). For each of these positions, the corresponding FSR voltage was recorded when grasping each material block: very soft foam, soft foam, medium-density foam, and rigid 3D-printed block.

The raw force signals obtained are displayed in Figure 4.2. These plots reveal clear differences in the FSR response depending on the stiffness of the material. For the very soft foam (a), the recorded voltages remain low across all closure levels, showing that even when the gripper is more tightly closed, the material absorbs most of the pressure. The soft foam (b) produces slightly higher voltages than the very soft foam, but the signal remains in a low range, reflecting



(a) Voltage recorded by the FSR when the robotic gripper closed around the very soft foam block at three different aperture levels.

(b) Voltage recorded by the FSR when the robotic gripper closed around the soft foam block at three different aperture levels.



(c) Voltage recorded by the FSR when the robotic gripper closed around the medium-density foam block at three different aperture levels.

(d) Voltage recorded by the FSR when the robotic gripper closed around the rigid 3D-printed block at three different aperture levels.

Figure 4.2: Raw voltage individual response graphs (Experiment 1 – first set):

its deformability. In contrast, the medium-density foam (c) shows a steeper increase in voltage, with clearer step-like responses at the three closure levels. Finally, the rigid 3D-printed block (d) exhibits the highest voltage values, with sharp and distinct steps that correspond directly to the programmed closures, as the material does not deform.

Comparing across the four materials, it is evident that softer foams yield lower voltage outputs, while stiffer materials elicit higher sensor responses under the same gripper positions. This demonstrates the sensor's ability to distinguish relative stiffness levels and provides the basis for mapping these differences into stimulation feedback.

4.2.2 Gripper opening profiling

The second analysis grouped the results by aperture level, rather than by material. This enabled a direct comparison of how different materials behaved under the same gripper closure strength. The results are illustrated in Figures 4.4 and 4.3, showing that for any given position of the gripper, the measured force increased proportionally with material stiffness. This confirms the sensitivity of the FSR to discriminate stiffness across conditions.

Figure 4.3 shows that the average FSR voltage varies systematically with both the aperture level of the robotic gripper and the stiffness of the grasped material. At the widest aperture (220), the voltages recorded for the very soft and soft foams are very low, below 0.5 V, reflecting their high deformability. In contrast, the medium-density foam and the rigid block produce substantially higher voltages, around 1.8 V and 2.7 V, respectively, showing that the sensor captures the difference in resistance offered by stiffer objects even at low closure forces.

At the medium aperture level (180), a similar pattern is observed, with soft foams still generating values well below 1 V, while the medium-density and rigid blocks elicit higher responses, exceeding 2 V and 3 V, respectively. Finally, at the tightest closure (140), all materials produce slightly higher voltages than in previous conditions, but the relative differences are maintained: softer foams remain below 1 V, while the medium-density and rigid blocks reach averages above 2.5 V.

This stepwise comparison highlights two key points. First, the FSR reliably distinguishes between soft and rigid materials, with voltages increasing as stiffness increases. Second, the changes across aperture levels are consistent, confirming that the gripper closure force can be mapped to different stimulation intensities in a reproducible way.

To facilitate interpretation, the data from Figure 4.4 was averaged and grouped by aperture level. It shows the raw response of the FSR across all three gripper aperture levels and for each material. Each elevation corresponds to the voltage output recorded when the robotic gripper closed around a material block at a given aperture setting. The differences in voltage are evident across materials: softer foams produce small responses (often below 0.5 V), while stiffer materials, particularly the rigid 3D-printed block, consistently generate higher voltages exceeding 3 V.

4.3 Experiment 2: Closed-loop stimulation with EAST device

The final experiment introduced electrical stimulation feedback. The same gripper positions were executed, this time with the force signals driving the EAST device in real time. A participant wore stimulation electrodes placed on the arm, and proportional stimulation was delivered according to the FSR readings.

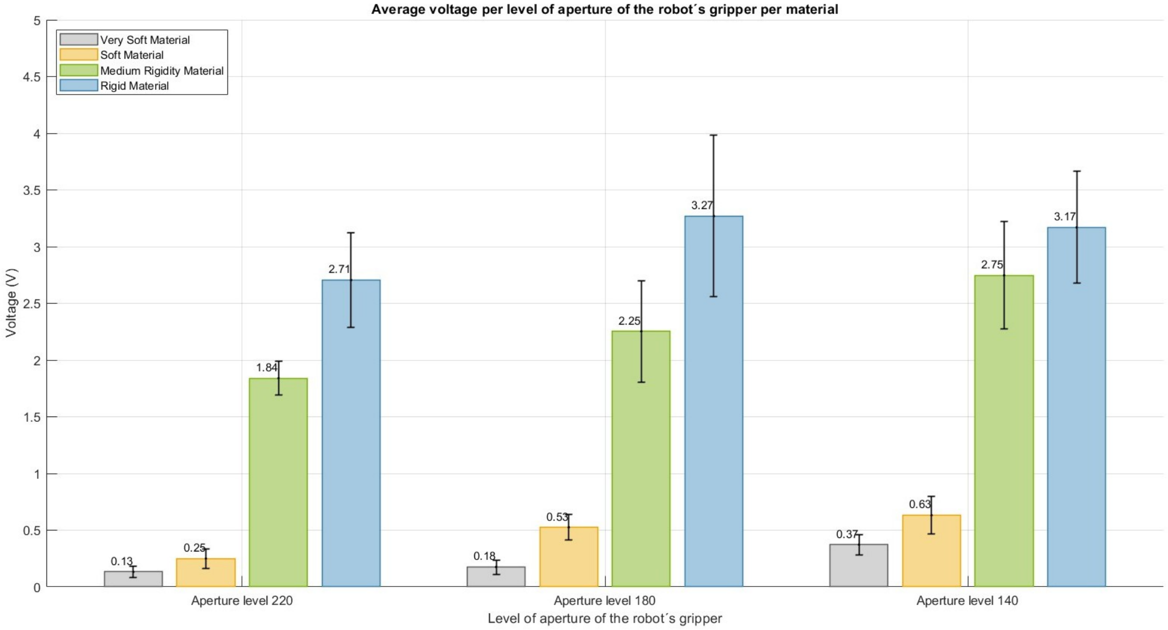


Figure 4.3: Post processed average voltage read in the FSR by aperture level of the robot gripper and by material. Aperture levels 220–140 refer to the servo motor position units in Arduino.

The stimulation signals, shown in Figure 4.5, displayed the expected staircase-like profile, due to the discrete resolution of the EAST device (0.5 mA increments). Importantly, the two participants in this experiment reported perceiving clear differences in stimulation intensity depending on the material stiffness, with softer objects producing weaker stimulation and the rigid block eliciting stronger sensations.

This confirms that the system was able to close the loop successfully, transforming physical interactions with objects into perceivable somatosensory feedback. While further validation with multiple users is required, these results constitute a first step toward enabling prosthesis users to distinguish material properties such as stiffness through non-invasive electrical stimulation.

Overall, the experimental results demonstrate the feasibility of the proposed feedback system. Beginning with a preliminary validation of the signal acquisition and stimulation pipeline, the study progressed to a detailed characterization of force responses across materials and gripper apertures, and finally to the delivery of proportional stimulation in real time. The system consistently captured differences in stiffness and translated them into distinguishable stimulation patterns, confirming its potential to restore a meaningful channel of somatosensory information. While these results represent an initial proof of concept obtained under controlled

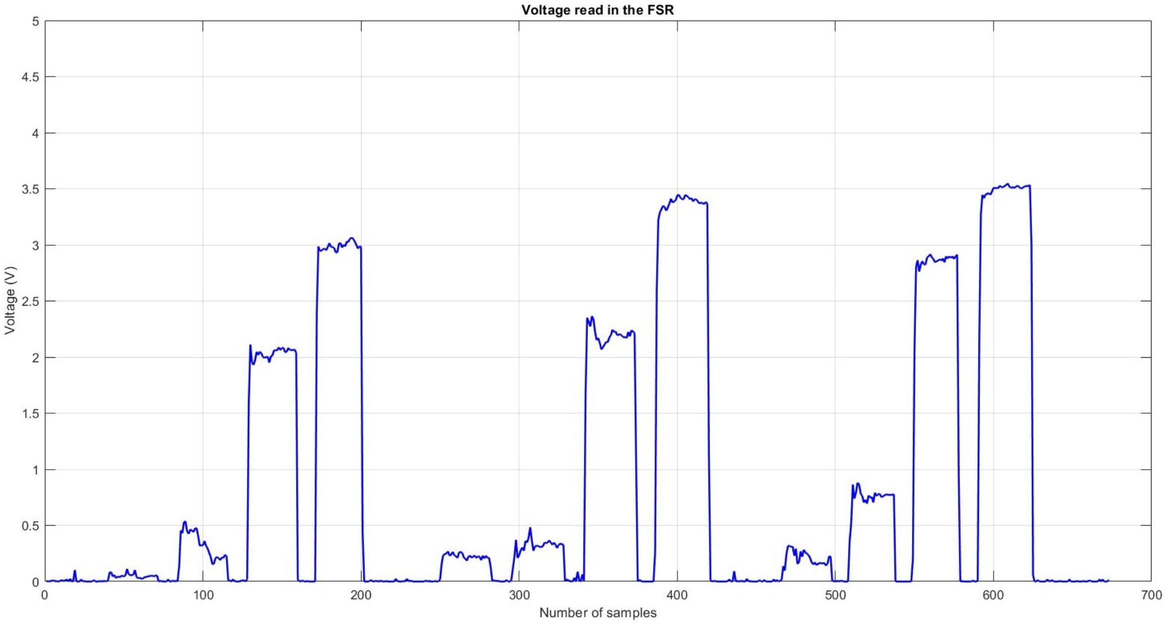


Figure 4.4: Raw voltage read in the FSR by aperture level of the robot gripper.

laboratory conditions, they provide a solid foundation for further evaluation with a broader range of users and experimental scenarios.

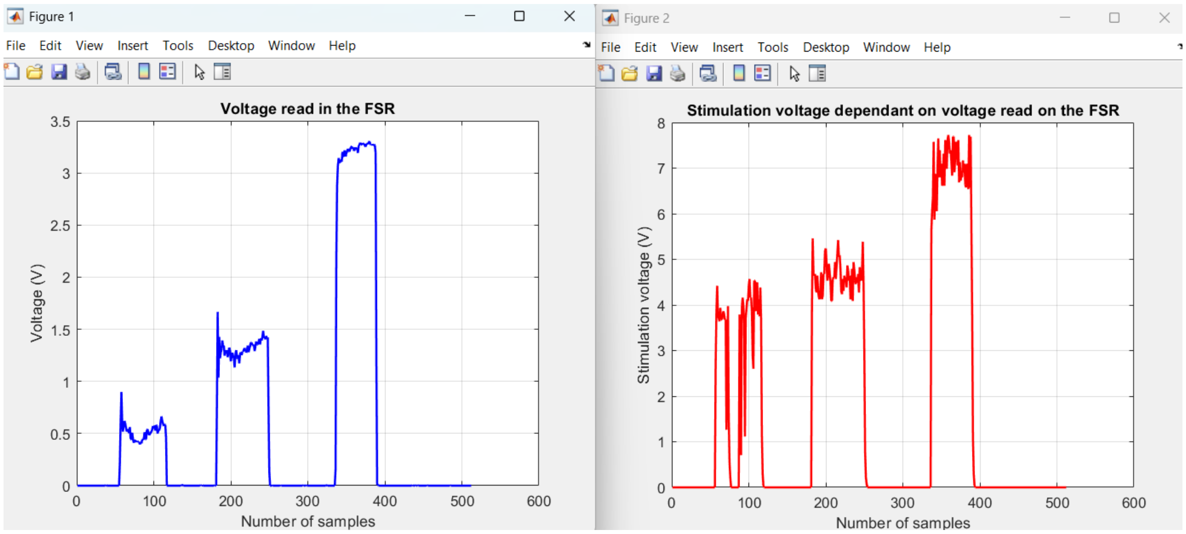


Figure 4.5: Closed-loop stimulation with EAST device on subject where 3 different materials were told apart.

5. Conclusion, discussion and future work

In this section, the main conclusions derived from the development and evaluation of the proposed system are presented. Furthermore, the discussion reflects on the advantages and limitations of the work carried out, while the final part outlines possible future research directions that could extend and improve the results achieved in this thesis.

5.1 Conclusion

The loss of a hand or part of the arm, means interrupting the closed-loop sensory feedback between the brain (motor control) and the hand (sensory feedback through the nerves). The lack of feedback requires significant cognitive efforts from the user to do basic gestures and daily activities.

The development and implementation of the feedback system developed in this Master's Thesis, represents a step towards addressing this limitation. By combining a force sensing resistor with a robotic arm and connecting its output signal to non-invasive electrical stimulation, the system was able to recreate part of the natural loop between action and sensation. The experiments showed that users could feel different levels of stiffness through changes in stimulation intensity, proving that meaningful sensory information can be delivered in real time.

The use of non-invasive transcutaneous electrical stimulation makes this approach practical, safe, and low-cost, compared to more invasive solutions such as implanted electrodes. Although the system is still at a proof-of-concept stage, it demonstrates that proportional feedback can be achieved without excessive complexity, offering a promising foundation for further development in prosthetic applications.

It is important to note that non-invasive transcutaneous electrical stimulation is widely used in clinical and research settings, particularly in pain management, neurorehabilitation and movement disorders, and is generally considered safe [31, 31]. The most common side effects are mild and temporary, such as tingling, itching, or slight skin redness under the electrode site, which disappear quickly after stimulation [31]. However, in this project, stimulation intensities are kept well below motor thresholds, ensuring safety by adjusting stimulation individually and monitoring user comfort throughout the session.

The aim of this Master's Thesis was to design, develop, and evaluate a non-invasive sensory feedback system to improve the user experience and functionality of myoelectric upper-limb prostheses. The following objectives were set at the beginning, and their fulfillment is summarized below:

- **Electrical stimulation method.** Achieved by configuring the EAST device to deliver proportional stimulation based on FSR-detected forces, within safe and sub-motor thresholds.
- **Human–Computer Interface control system.** Implemented through the integration of the PhantomX robotic arm, FSR sensor, Arduino board, and EAST stimulator, enabling real-time interaction between prosthesis simulator and feedback system.
- **Software development.** MATLAB scripts and Arduino code were created for synchronized signal acquisition, processing, robotic actuation, and stimulation control.
- **System evaluation.** Laboratory experiments with materials of varying stiffness showed that the system could reliably distinguish differences in force, confirming its feasibility for restoring somatosensory feedback in prosthetic use.

5.2 Future work

While the present project demonstrates the feasibility of using force-dependent electrical stimulation to provide somatosensory feedback in upper-limb prosthetics, the following points outline potential directions that could enhance the functionality of the proposed approach.

- **Expand user testing.** Conduct experiments with a larger and more diverse group of participants, including individuals with upper-limb amputations, to validate usability and comfort.
- **Refine stimulation strategies.** Explore alternative combination of parameters for stimulation (amplitude modulation, frequency, pulse duration...) to analyze the effect on the patient. Also, varying the transfer function (polynomial, exponential, logaritmical, asyntotical...) that correlates the force and the stimulation, can convey a different outcome.
- **Alternative stimulation hardware.** The discrete resolution of the EAST device resulted in a staggered stimulation output, which, while functional, may limit the naturalness of the sensation. Future work should explore alternative coding strategies, higher-resolution devices, and other feedback approaches to improve intuitiveness and embodiment.
- **Multi-sensor and multi-site stimulation mapping.** Develop experiments using several force sensors placed at strategic locations across the prosthetic hand to capture interesting interaction data. This would allow the stimulation to be mapped more

precisely to specific nerves, muscles, or neural pathways in the residual limb. Such an approach could enable more localized and personalized feedback, improving the correspondence between different hand areas and their associated sensations, and ultimately making the feedback system more intuitive and natural.

- **Integration with EMG control.** A natural next step is to couple the feedback system with myoelectric prosthesis to close the bidirectional loop. In this way, the user's residual muscle activity would generate motor commands to drive the prosthetic hand, while the force sensors embedded in the prosthesis would provide proportional electrical stimulation as sensory feedback. This closed-loop configuration would replicate the natural bidirectional communication of the human sensorimotor system, reducing cognitive load.
- **Task-based evaluation.** Assess the system in more functional scenarios, such as grasping and manipulating everyday objects, to evaluate its impact on usability in real-life tasks.
- **Long-term usability studies.** Investigate comfort, safety, and learning effects over extended use, to analyze whether users adapt and improve their discrimination ability with training.

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Annexes

A Ethical economic, social and environmental aspects

A.1 Introduction

This Master's Thesis explores the development of a feedback system for upper-limb prostheses, aiming to restore part of the somatosensory loop by integrating a force sensing resistor, a robotic arm, and transcutaneous electrical stimulation. The project addresses a key limitation in current prosthetic devices: the lack of sensory feedback, which often reduces usability and user acceptance. By working on solutions that improve intuitiveness and embodiment, this research is directly related to social and ethical challenges such as inclusivity, quality of life, and accessibility for people with limb loss. Furthermore, it raises questions about economic feasibility, equitable access to healthcare technologies, and the sustainability of implementing such systems in clinical and everyday settings.

A.2 Description of Relevant Impacts Related to the Project

The project has several potential impacts across social, economic, ethical and environmental domains.

- **Societal impact.** Improving prosthetic usability has the potential to increase autonomy and quality of life for individuals with upper-limb amputations. This contributes to social inclusion by allowing users to participate more fully in work, daily activities, and social life. The main stakeholders identified and considered are patients, healthcare providers, rehabilitation specialists, prosthetic manufacturers, and policy makers.
- **Economic impact.** Current prosthetic systems remain costly and restrict accessibility to a minority of patients. Although this Master's Thesis is in the research stage, the process of moving it from the lab to the clinic, including design optimization, clinical testing,

regulatory approval, manufacturing, and distribution; must consider keeping costs low enough, so that the final solution is not restricted to high-income users. Otherwise, even if the technology works very well, very few patients will have access to it.

- **Ethical impact.** Patient safety, comfort and informed consent regarding the use of electrical stimulation are key factors in this aspect. Respecting individual differences in sensitivity, pain thresholds, and medical conditions is essential to ensure the technology is not harmful. Additionally, ethical responsibility extends to equitable access: such technology should aim to reduce, rather than widen, healthcare inequalities.
- **Environmental impact.** Although the direct environmental footprint of this prototype is limited, the expansion of prosthetic technology production requires sustainable choices in material use, electronic design and energy consumption. In addition, considerations of device durability and recyclability are relevant to reduce long-term waste.

A.3 Detailed Analysis of One of the Principal Impacts

A detailed focus can be placed on the economic accessibility of prosthetic technologies. Currently, many advanced prosthetic devices range from $ 10,000 to more than $ 40,000, which poses a barrier to adoption. Even if sensory feedback technologies are proved effective, they will have limited real-world impact if they are not affordable to the majority of users. Therefore, research must aim to not only advance technical performance but also to develop **cost-effective and scalable designs**. The use of non-invasive feedback (such as surface electrodes and low-cost sensors) is a step in this direction, since it avoids costly surgical interventions and minimizes additional infrastructure. Collaborations with healthcare systems and insurance providers will be essential to ensure that these innovations can reach the patients who need them most.

A.4 Conclusions

From an ethical, societal, economic, and environmental perspective, this project demonstrates a commitment to responsible engineering practice. By prioritizing patient safety and comfort, it aligns with ethical principles of beneficence and non-maleficence. Its societal value lies in promoting autonomy and inclusivity for amputees. Economically, the work highlights the importance of affordability and scalability as prerequisites for real-world impact. Environmentally, it points toward the need for sustainable material use and design practices as the technology develops further.

Applying responsible criteria has added value to this project. It broadens its scope beyond technical feasibility, aligning it within the context of patient well-being, equity of access, and long-term sustainability. These considerations are essential to ensure that advances in prosthetic feedback systems translate into meaningful and responsible innovation in healthcare.

B Financial Budget

The following table presents the estimated costs associated with the development of the Master's Thesis.

PERSONNEL COSTS (direct costs)		**Hours**	**Hourly cost**	**Total**
		450	15 €	**6.750 €**
MATERIAL RESOURCES COSTS (direct costs, DC)	**Purchase price**	**Months of use**	**Depreciation (in years)**	**Total**
Personal computer	900,00 €	6	5	**90,00 €**
Tablet	500,00 €	6	5	**50,00 €**
PhantomX Reactor Robot (research use)	469,67 €	6	10	**23,48 €**
EAST stimualtion device	2.500,00 €	6	10	**125,00 €**
Arduino UNO board	29,30 €	6	5	**2,93 €**
Force Sensing Resistor (FSR)	9,00 €	6	1	**4,50 €**
Electronic components and cables	10,20 €	6	1	**5,10 €**
TOTAL COSTS OF MATERIAL RESOURCES	**301,01 €**			
GENERAL COSTS (indirect costs)	15%	on CD		**1.057,65 €**
INDUSTRIAL BENEFIT	6%	on DC+IC		**486,52 €**
CONSUMABLES				
Gelified adhesive electrodes with banana cables (squared and rounded)				**6,75 €**
3D printed test blocks (materials + printer time)				**30,00 €**
SUBTOTAL BUDGET				**8.595,18 €**
VAT			21%	**1.804,99 €**
TOTAL BUDGET				**10.400,16 €**

Electronic components and cables include x3 100 kΩ resistors, x1 10 kΩ resistor, x1 47 Ω resistor, x1 LF356N Operational Amplifier, x1 120 pF capacitor, x1 680 nF capacitor, x1 1N4148 diode, jumper and crocodile clip cables.

C Code

The code developed for this application can be found at `https://github.com/RobolaboTFT/martaz`.